HISTORY OF ASTRONOMY

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PREFACE

An attempt has been made in these pages to trace the evolution of intellectual thought in the progress of astronomical discovery, and, by recognising the different points of view of the different ages, to give due credit even to the ancients. No one can expect, in a history of astronomy of limited size, to find a treatise on "practical" or on "theoretical astronomy," nor a complete "descriptive astronomy," and still less a book on "speculative astronomy." Something of each of these is essential, however, for tracing the progress of thought and knowledge which it is the object of this History to describe.

The progress of human knowledge is measured by the increased habit of looking at facts from new points of view, as much as by the accumulation of facts. The mental capacity of one age does not seem to differ from that of other ages; but it is the imagination of new points of view that gives a wider scope to that capacity. And this is cumulative, and therefore progressive. Aristotle viewed the solar system as a geometrical problem; Kepler and Newton converted the point of view into a dynamical one. Aristotle's mental capacity to understand the meaning of facts or to criticise a train of reasoning may have been equal to that of Kepler or Newton, but the point of view was different.

Then, again, new points of view are provided by the invention of new methods in that system of logic which we call mathematics. All that mathematics can do is to assure us that a statement A is equivalent to statements B, C, D, or is one of the facts expressed by the statements B, C, D; so that we may know, if B, C, and D are true, then A is true. To many people our inability to understand all that is contained in

statements B, C, and D, without the cumbrous process of a mathematical demonstration, proves the feebleness of the human mind as a logical machine. For it required the new point of view imagined by Newton's analysis to enable people to see that, so far as planetary orbits are concerned, Kepler's three laws (B, C, D) were identical with Newton's law of gravitation (A). No one recognises more than the mathematical astronomer this feebleness of the human intellect, and no one is more conscious of the limitations of the logical process called mathematics, which even now has not solved directly the problem of only three bodies.

These reflections, arising from the writing of this History, go to explain the invariable humility of the great mathematical astronomers. Newton's comparison of himself to the child on the seashore applies to them all. As each new discovery opens up, it may be, boundless oceans for investigation, for wonder, and for admiration, the great astronomers, refusing to accept mere hypotheses as true, have founded upon these discoveries a science as exact in its observation of facts as in theories. So it is that these men, who have built up the most sure and most solid of all the sciences, refuse to invite others to join them in vain speculation. The writer has, therefore, in this short History, tried to follow that great master, Airy, whose pupil he was, and the key to whose character was exactness and accuracy; and he recognises that Science is impotent except in her own limited sphere.

It has been necessary to curtail many parts of the History in the attempt–perhaps a hopeless one–to lay before the reader in a limited space enough about each age to illustrate its tone and spirit, the ideals of the workers, the gradual addition of new points of view and of new means of investigation.

It would, indeed, be a pleasure to entertain the hope that these pages might, among new recruits, arouse an interest in the greatest of all the sciences, or that those who have handled the theoretical or practical side might be led by them to read in the original some of the classics of astronomy. Many students have much compassion for the schoolboy of to-day, who is not allowed the luxury of learning the art of reasoning from him who still remains pre-eminently its greatest exponent, Euclid. These students pity also the man of to-morrow, who is not to be allowed to read, in the original Latin of the brilliant Kepler, how he was able–by observations taken from a moving platform, the earth, of the directions of a moving object, Mars–to deduce the exact shape of the path of each of these planets, and their actual positions on these paths at any time. Kepler's masterpiece is one of the most interesting books that was ever written, combining wit, imagination, ingenuity, and certainty.

Lastly, it must be noted that, as a History of England cannot deal with the present Parliament, so also the unfinished researches and untested hypotheses of many well-known astronomers of to-day cannot be

included among the records of the History of Astronomy. The writer regrets the necessity that thus arises of leaving without mention the names of many who are now making history in astronomical work.

G. F.
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BOOK I. THE GEOMETRICAL PERIOD

1. PRIMITIVE ASTRONOMY AND ASTROLOGY.

The growth of intelligence in the human race has its counterpart in that of the individual, especially in the earliest stages. Intellectual activity and the development of reasoning powers are in both cases based upon the accumulation of experiences, and on the comparison, classification, arrangement, and nomenclature of these experiences. During the infancy of each the succession of events can be watched, but there can be no _Ã priori_ anticipations. Experience alone, in both cases, leads to the idea of cause and effect as a principle that seems to dominate our present universe, as a rule for predicting the course of events, and as a guide to the choice of a course of action. This idea of cause and effect is the most potent factor in developing the history of the human race, as of the individual.

In no realm of nature is the principle of cause and effect more conspicuous than in astronomy; and we fall into the habit of thinking of its laws as not only being unchangeable in our universe, but necessary to the conception of any universe that might have been substituted in its place. The first inhabitants of the world were compelled to accommodate their acts to the daily and annual alternations of light and darkness and of heat and cold, as much as to the irregular changes of weather, attacks of disease, and the fortune of war. They soon came to regard the influence of the sun, in connection with light and heat, as a cause. This led to a search for other signs in the heavens. If the appearance of a comet was sometimes noted simultaneously with the death of a great ruler, or an eclipse with a scourge of plague, these might well be looked upon as causes in the same sense that the veering or backing of the wind is regarded as a cause of fine or foul weather.

For these reasons we find that the earnest men of all ages have recorded the occurrence of comets, eclipses, new stars, meteor showers, and remarkable conjunctions of the planets, as well as plagues and famines, floods and droughts, wars and the deaths of great rulers. Sometimes they thought they could trace connections which might lead them to say that a comet presaged famine, or an eclipse war.

Even if these men were sometimes led to evolve laws of cause and

effect which now seem to us absurd, let us be tolerant, and gratefully acknowledge that these astrologers, when they suggested such "working hypotheses," were laying the foundations of observation and deduction.

If the ancient ChaldÃans gave to the planetary conjunctions an influence over terrestrial events, let us remember that in our own time people have searched for connection between terrestrial conditions and periods of unusual prevalence of sun spots; while De la Rue, Loewy, and Balfour Stewart[1] thought they found a connection between sun-spot displays and the planetary positions. Thus we find scientific men, even in our own time, responsible for the belief that storms in the Indian Ocean, the fertility of German vines, famines in India, and high or low Nile-floods in Egypt follow the planetary positions.

And, again, the desire to foretell the weather is so laudable that we cannot blame the ancient Greeks for announcing the influence of the moon with as much confidence as it is affirmed in Lord Wolseley's _Soldier's Pocket Book_.

Even if the scientific spirit of observation and deduction (astronomy) has sometimes led to erroneous systems for predicting terrestrial events (astrology), we owe to the old astronomer and astrologer alike the deepest gratitude for their diligence in recording astronomical events. For, out of the scanty records which have survived the destructive acts of fire and flood, of monarchs and mobs, we have found much that has helped to a fuller knowledge of the heavenly motions than was possible without these records.

So Hipparchus, about 150 B.C., and Ptolemy a little later, were able to use the observations of ChaldÃan astrologers, as well as those of Alexandrian astronomers, and to make some discoveries which have helped the progress of astronomy in all ages. So, also, Mr. Cowell[2] has examined the marks made on the baked bricks used by the ChaldÃans for recording the eclipses of 1062 B.C. and 762 B.C.; and has thereby been enabled, in the last few years, to correct the lunar tables of Hansen, and to find a more accurate value for the secular acceleration of the moon's longitude and the node of her orbit than any that could be obtained from modern observations made with instruments of the highest precision.

So again, Mr. Hind [3] was enabled to trace back the period during which Halley's comet has been a member of the solar system, and to identify it in the Chinese observations of comets as far back as 12 B.C. Cowell and Cromellin extended the date to 240 B.C. In the same way the comet 1861.i. has been traced back in the Chinese records to 617 A.D. [4]

The theoretical views founded on Newton's great law of universal gravitation led to the conclusion that the inclination of the earth's

equator to the plane of her orbit (the obliquity of the ecliptic) has been diminishing slowly since prehistoric times; and this fact has been confirmed by Egyptian and Chinese observations on the length of the shadow of a vertical pillar, made thousands of years before the Christian era, in summer and winter.

There are other reasons why we must be tolerant of the crude notions of the ancients. The historian, wishing to give credit wherever it may be due, is met by two difficulties. Firstly, only a few records of very ancient astronomy are extant, and the authenticity of many of these is open to doubt. Secondly, it is very difficult to divest ourselves of present knowledge, and to appreciate the originality of thought required to make the first beginnings.

With regard to the first point, we are generally dependent upon histories written long after the events. The astronomy of Egyptians, Babylonians, and Assyrians is known to us mainly through the Greek historians, and for information about the Chinese we rely upon the researches of travellers and missionaries in comparatively recent times. The testimony of the Greek writers has fortunately been confirmed, and we now have in addition a mass of facts translated from the original sculptures, papyri, and inscribed bricks, dating back thousands of years.

In attempting to appraise the efforts of the beginners we must remember that it was natural to look upon the earth (as all the first astronomers did) as a circular plane, surrounded and bounded by the heaven, which was a solid vault, or hemisphere, with its concavity turned downwards. The stars seemed to be fixed on this vault; the moon, and later the planets, were seen to crawl over it. It was a great step to look on the vault as a hollow sphere carrying the sun too. It must have been difficult to believe that at midday the stars are shining as brightly in the blue sky as they do at night. It must have been difficult to explain how the sun, having set in the west, could get back to rise in the east without being seen _if_ it was always the same sun. It was a great step to suppose the earth to be spherical, and to ascribe the diurnal motions to its rotation. Probably the greatest step ever made in astronomical theory was the placing of the sun, moon, and planets at different distances from the earth instead of having them stuck on the vault of heaven. It was a transition from "flatland" to a space of three dimensions.

Great progress was made when systematic observations began, such as following the motion of the moon and planets among the stars, and the inferred motion of the sun among the stars, by observing their _heliacal risings_–i.e., the times of year when a star would first be seen to rise at sunrise, and when it could last be seen to rise at sunset. The grouping of the stars into constellations and recording their places was a useful observation. The theoretical prediction of eclipses of the sun and moon, and of the motions of the

planets among the stars, became later the highest goal in astronomy.

To not one of the above important steps in the progress of astronomy can we assign the author with certainty. Probably many of them were independently taken by Chinese, Indian, Persian, Tartar, Egyptian, Babylonian, Assyrian, Phoenician, and Greek astronomers. And we have not a particle of information about the discoveries, which may have been great, by other peoples–by the Druids, the Mexicans, and the Peruvians, for example.

We do know this, that all nations required to have a calendar. The solar year, the lunar month, and the day were the units, and it is owing to their incommensurability that we find so many calendars proposed and in use at different times. The only object to be attained by comparing the chronologies of ancient races is to fix the actual dates of observations recorded, and this is not a part of a history of astronomy.

In conclusion, let us bear in mind the limited point of view of the ancients when we try to estimate their merit. Let us remember that the first astronomy was of two dimensions; the second astronomy was of three dimensions, but still purely geometrical. Since Kepler's day we have had a dynamical astronomy.

FOOTNOTES:

[1] Trans. R. S. E., xxiii. 1864, p. 499, _On Sun Spots_, etc., by B. Stewart. Also Trans. R. S. 1860-70. Also Prof. Ernest Brown, in _R. A. S. Monthly Notices_, 1900.

[2] _R. A. S. Monthly Notices_, Sup.; 1905.

[Illustration: CHALDÃAN BAKED BRICK OR TABLET, _Obverse and reverse
sides_, Containing record of solar eclipse, 1062 B.C., used lately by Cowell for rendering the lunar theory more accurate than was possible by finest modern observations. (British Museum collection, No. 35908.)]

[3] _R. A. S. Monthly Notices_, vol. x., p. 65.

[4] R. S. E. Proc., vol. x., 1880.

2. ANCIENT ASTRONOMY–THE CHINESE AND CHALDÃANS.

The last section must have made clear the difficulties the way of assigning to the ancient nations their proper place in the development of primitive notions about astronomy. The fact that some alleged observations date back to a period before the Chinese had invented the art of writing leads immediately to the question how far tradition can

be trusted.

Our first detailed knowledge was gathered in the far East by travellers, and by the Jesuit priests, and was published in the eighteenth century. The Asiatic Society of Bengal contributed translations of Brahmin literature. The two principal sources of knowledge about Chinese astronomy were supplied, first by Father Souciet, who in 1729 published _Observations Astronomical, Geographical, Chronological, and Physical_, drawn from ancient Chinese books; and later by Father Moyriac-de-Mailla, who in 1777-1785 published _Annals of the Chinese Empire, translated from Tong-Kien-Kang-Mou_.

Bailly, in his _Astronomie Ancienne_ (1781), drew, from these and other sources, the conclusion that all we know of the astronomical learning of the Chinese, Indians, ChaldÃans, Assyrians, and Egyptians is but the remnant of a far more complete astronomy of which no trace can be found.

Delambre, in his _Histoire de l'Astronomie Ancienne_ (1817), ridicules the opinion of Bailly, and considers that the progress made by all of these nations is insignificant.

It will be well now to give an idea of some of the astronomy of the ancients not yet entirely discredited. China and Babylon may be taken as typical examples.

China.–It would appear that Fohi, the first emperor, reigned about 2952 B.C., and shortly afterwards Yu-Chi made a sphere to represent the motions of the celestial bodies. It is also mentioned, in the book called Chu-King, supposed to have been written in 2205 B.C., that a similar sphere was made in the time of Yao (2357 B.C.).[1] It is said that the Emperor Chueni (2513 B.C.) saw five planets in conjunction the same day that the sun and moon were in conjunction. This is discussed by Father Martin (MSS. of De Lisle); also by M. Desvignolles (Mem. Acad. Berlin, vol. iii., p. 193), and by M. Kirsch (ditto, vol. v., p. 19), who both found that Mars, Jupiter, Saturn, and Mercury were all between the eleventh and eighteenth degrees of Pisces, all visible together in the evening on February 28th 2446 B.C., while on the same day the sun and moon were in conjunction at 9 a.m., and that on March 1st the moon was in conjunction with the other four planets. But this needs confirmation.

Yao, referred to above, gave instructions to his astronomers to determine the positions of the solstices and equinoxes, and they reported the names of the stars in the places occupied by the sun at these seasons, and in 2285 B.C. he gave them further orders. If this account be true, it shows a knowledge that the vault of heaven is a complete sphere, and that stars are shining at mid-day, although eclipsed by the sun's brightness.

It is also asserted, in the book called _Chu-King_, that in the time of Yao the year was known to have 365Â days, and that he adopted 365 days and added an intercalary day every four years (as in the Julian Calendar). This may be true or not, but the ancient Chinese certainly seem to have divided the circle into 365 degrees. To learn the length of the year needed only patient observation–a characteristic of the Chinese; but many younger nations got into a terrible mess with their calendar from ignorance of the year's length.

It is stated that in 2159 B.C. the royal astronomers Hi and Ho failed to predict an eclipse. It probably created great terror, for they were executed in punishment for their neglect. If this account be true, it means that in the twenty-second century B.C. some rule for calculating eclipses was in use. Here, again, patient observation would easily lead to the detection of the eighteen-year cycle known to the Chaldeans as the _Saros_. It consists of 235 lunations, and in that time the pole of the moon's orbit revolves just once round the pole of the ecliptic, and for this reason the eclipses in one cycle are repeated with very slight modification in the next cycle, and so on for many centuries.

It may be that the neglect of their duties by Hi and Ho, and their punishment, influenced Chinese astronomy; or that the succeeding records have not been available to later scholars; but the fact remains that–although at long intervals observations were made of eclipses, comets, and falling stars, and of the position of the solstices, and of the obliquity of the ecliptic–records become rare, until 776 B.C., when eclipses began to be recorded once more with some approach to continuity. Shortly afterwards notices of comets were added. Biot gave a list of these, and Mr. John Williams, in 1871, published _Observations of Comets from 611 B.C. to 1640 A.D., Extracted from the Chinese Annals_.

With regard to those centuries concerning which we have no astronomical Chinese records, it is fair to state that it is recorded that some centuries before the Christian era, in the reign of Tsin-Chi-Hoang, all the classical and scientific books that could be found were ordered to be destroyed. If true, our loss therefrom is as great as from the burning of the Alexandrian library by the Caliph Omar. He burnt all the books because he held that they must be either consistent or inconsistent with the Koran, and in the one case they were superfluous, in the other case objectionable.

ChaldÃans.–Until the last half century historians were accustomed to look back upon the Greeks, who led the world from the fifth to the third century B.C., as the pioneers of art, literature, and science. But the excavations and researches of later years make us more ready to grant that in science as in art the Greeks only developed what they derived from the Egyptians, Babylonians, and

Assyrians. The Greek historians said as much, in fact; and modern commentators used to attribute the assertion to undue modesty. Since, however, the records of the libraries have been unearthed it has been recognised that the Babylonians were in no way inferior in the matter of original scientific investigation to other races of the same era.

The ChaldÃans, being the most ancient Babylonians, held the same station and dignity in the State as did the priests in Egypt, and spent all their time in the study of philosophy and astronomy, and the arts of divination and astrology. They held that the world of which we have a conception is an eternal world without any beginning or ending, in which all things are ordered by rules supported by a divine providence, and that the heavenly bodies do not move by chance, nor by their own will, but by the determinate will and appointment of the gods. They recorded these movements, but mainly in the hope of tracing the will of the gods in mundane affairs. Ptolemy (about 130 A.D.) made use of Babylonian eclipses in the eighth century B.C. for improving his solar and lunar tables.

Fragments of a library at Agade have been preserved at Nineveh, from which we learn that the star-charts were even then divided into constellations, which were known by the names which they bear to this day, and that the signs of the zodiac were used for determining the courses of the sun, moon, and of the five planets Mercury, Venus, Mars, Jupiter, and Saturn.

We have records of observations carried on under Asshurbanapal, who sent astronomers to different parts to study celestial phenomena. Here is one:–

To the Director of Observations,–My Lord, his humble servant Nabushum-iddin, Great Astronomer of Nineveh, writes thus: "May Nabu and Marduk be propitious to the Director of these Observations, my Lord. The fifteenth day we observed the Node of the moon, and the moon was eclipsed."

The Phoenicians are supposed to have used the stars for navigation, but there are no records. The Egyptian priests tried to keep such astronomical knowledge as they possessed to themselves. It is probable that they had arbitrary rules for predicting eclipses. All that was known to the Greeks about Egyptian science is to be found in the writings of Diodorus Siculus. But confirmatory and more authentic facts have been derived from late explorations. Thus we learn from E. B. Knobel[2] about the Jewish calendar dates, on records of land sales in Aramaic papyri at Assuan, translated by Professor A. H. Sayce and A. E. Cowley, (1) that the lunar cycle of nineteen years was used by the Jews in the fifth century B.C. [the present reformed Jewish calendar dating from the fourth century A.D.], a date a "little more than a century after the grandfathers and great-grandfathers of those whose business is recorded had fled into Egypt with Jeremiah" (Sayce);

and (2) that the order of intercalation at that time was not dissimilar to that in use at the present day.

Then again, Knobel reminds us of "the most interesting discovery a few years ago by Father Strassmeier of a Babylonian tablet recording a partial lunar eclipse at Babylon in the seventh year of Cambyses, on the fourteenth day of the Jewish month Tammuz." Ptolemy, in the Almagest (Suntaxis), says it occurred in the seventh year of Cambyses, on the night of the seventeenth and eighteenth of the Egyptian month Phamenoth. PingrÃ and Oppolzer fix the date July 16th, 533 B.C. Thus are the relations of the chronologies of Jews and Egyptians established by these explorations.

FOOTNOTES:

[1] These ancient dates are uncertain.

[2] _R. A. S. Monthly Notices_, vol. lxviii., No. 5, March, 1908.

3. ANCIENT GREEK ASTRONOMY.

We have our information about the earliest Greek astronomy from Herodotus (born 480 B.C.). He put the traditions into writing. Thales (639-546 B.C.) is said to have predicted an eclipse, which caused much alarm, and ended the battle between the Medes and Lydians. Airy fixed the date May 28th, 585 B.C. But other modern astronomers give different dates. Thales went to Egypt to study science, and learnt from its priests the length of the year (which was kept a profound secret!), and the signs of the zodiac, and the positions of the solstices. He held that the sun, moon, and stars are not mere spots on the heavenly vault, but solids; that the moon derives her light from the sun, and that this fact explains her phases; that an eclipse of the moon happens when the earth cuts off the sun's light from her. He supposed the earth to be flat, and to float upon water. He determined the ratio of the sun's diameter to its orbit, and apparently made out the diameter correctly as half a degree. He left nothing in writing.

His successors, Anaximander (610-547 B.C.) and Anaximenes (550-475 B.C.), held absurd notions about the sun, moon, and stars, while Heraclitus (540-500 B.C.) supposed that the stars were lighted each night like lamps, and the sun each morning. Parmenides supposed the earth to be a sphere.

Pythagoras (569-470 B.C.) visited Egypt to study science. He deduced his system, in which the earth revolves in an orbit, from fantastic first principles, of which the following are examples: "The circular motion is the most perfect motion," "Fire is more worthy than earth," "Ten is the perfect number." He wrote nothing, but is supposed to have said that the earth, moon, five planets, and fixed stars all revolve round the sun, which itself revolves round an imaginary central fire

called the Antichthon. Copernicus in the sixteenth century claimed Pythagoras as the founder of the system which he, Copernicus, revived.

Anaxagoras (born 499 B.C.) studied astronomy in Egypt. He explained the return of the sun to the east each morning by its going under the flat earth in the night. He held that in a solar eclipse the moon hides the sun, and in a lunar eclipse the moon enters the earth's shadow–both excellent opinions. But he entertained absurd ideas of the vortical motion of the heavens whisking stones into the sky, there to be ignited by the fiery firmament to form stars. He was prosecuted for this unsettling opinion, and for maintaining that the moon is an inhabited earth. He was defended by Pericles (432 B.C.).

Solon dabbled, like many others, in reforms of the calendar. The common year of the Greeks originally had 360 days–twelve months of thirty days. Solon's year was 354 days. It is obvious that these erroneous years would, before long, remove the summer to January and the winter to July. To prevent this it was customary at regular intervals to intercalate days or months. Meton (432 B.C.) introduced a reform based on the nineteen-year cycle. This is not the same as the Egyptian and Chaldean eclipse cycle called _Saros_ of 223 lunations, or a little over eighteen years. The Metonic cycle is 235 lunations or nineteen years, after which period the sun and moon occupy the same position relative to the stars. It is still used for fixing the date of Easter, the number of the year in Melon's cycle being the golden number of our prayer-books. Melon's system divided the 235 lunations into months of thirty days and omitted every sixty-third day. Of the nineteen years, twelve had twelve months and seven had thirteen months.

Callippus (330 B.C.) used a cycle four times as long, 940 lunations, but one day short of Melon's seventy-six years. This was more correct.

Eudoxus (406-350 B.C.) is said to have travelled with Plato in Egypt. He made astronomical observations in Asia Minor, Sicily, and Italy, and described the starry heavens divided into constellations. His name is connected with a planetary theory which as generally stated sounds most fanciful. He imagined the fixed stars to be on a vault of heaven; and the sun, moon, and planets to be upon similar vaults or spheres, twenty-six revolving spheres in all, the motion of each planet being resolved into its components, and a separate sphere being assigned for each component motion. Callippus (330 B.C.) increased the number to thirty-three. It is now generally accepted that the real existence of these spheres was not suggested, but the idea was only a mathematical conception to facilitate the construction of tables for predicting the places of the heavenly bodies.

Aristotle (384-322 B.C.) summed up the state of astronomical knowledge in his time, and held the earth to be fixed in the centre of the world.

Nicetas, Heraclides, and Ecphantes supposed the earth to revolve on its axis, but to have no orbital motion.

The short epitome so far given illustrates the extraordinary deductive methods adopted by the ancient Greeks. But they went much farther in the same direction. They seem to have been in great difficulty to explain how the earth is supported, just as were those who invented the myth of Atlas, or the Indians with the tortoise. Thales thought that the flat earth floated on water. Anaxagoras thought that, being flat, it would be buoyed up and supported on the air like a kite. Democritus thought it remained fixed, like the donkey between two bundles of hay, because it was equidistant from all parts of the containing sphere, and there was no reason why it should incline one way rather than another. Empedocles attributed its state of rest to centrifugal force by the rapid circular movement of the heavens, as water is stationary in a pail when whirled round by a string. Democritus further supposed that the inclination of the flat earth to the ecliptic was due to the greater weight of the southern parts owing to the exuberant vegetation.

For further references to similar efforts of imagination the reader is referred to Sir George Cornwall Lewis's _Historical Survey of the Astronomy of the Ancients_; London, 1862. His list of authorities is very complete, but some of his conclusions are doubtful. At p. 113 of that work he records the real opinions of Socrates as set forth by Xenophon; and the reader will, perhaps, sympathise with Socrates in his views on contemporary astronomy:–

With regard to astronomy he [Socrates] considered a knowledge of it desirable to the extent of determining the day of the year or month, and the hour of the night, ... but as to learning the courses of the stars, to be occupied with the planets, and to inquire about their distances from the earth, and their orbits, and the causes of their motions, he strongly objected to such a waste of valuable time. He dwelt on the contradictions and conflicting opinions of the physical philosophers, ... and, in fine, he held that the speculators on the universe and on the laws of the heavenly bodies were no better than madmen (_Xen_. _Mem_, i. 1, 11-15).

Plato (born 429 B.C.), the pupil of Socrates, the fellow-student of Euclid, and a follower of Pythagoras, studied science in his travels in Egypt and elsewhere. He was held in so great reverence by all learned men that a problem which he set to the astronomers was the keynote to all astronomical investigation from this date till the time of Kepler in the sixteenth century. He proposed to astronomers _the problem of representing the courses of the planets by circular and uniform motions_.

Systematic observation among the Greeks began with the rise of the

Alexandrian school. Aristillus and Timocharis set up instruments and fixed the positions of the zodiacal stars, near to which all the planets in their orbits pass, thus facilitating the determination of planetary motions. Aristarchus (320-250 B.C.) showed that the sun must be at least nineteen times as far off as the moon, which is far short of the mark. He also found the sun's diameter, correctly, to be half a degree. Eratosthenes (276-196 B.C.) measured the inclination to the equator of the sun's apparent path in the heavens–i.e., he measured the obliquity of the ecliptic, making it 23Â 51', confirming our knowledge of its continuous diminution during historical times. He measured an arc of meridian, from Alexandria to Syene (Assuan), and found the difference of latitude by the length of a shadow at noon, summer solstice. He deduced the diameter of the earth, 250,000 stadia. Unfortunately, we do not know the length of the stadium he used.

Hipparchus (190-120 B.C.) may be regarded as the founder of observational astronomy. He measured the obliquity of the ecliptic, and agreed with Eratosthenes. He altered the length of the tropical year from 365 days, 6 hours to 365 days, 5 hours, 53 minutes–still four minutes too much. He measured the equation of time and the irregular motion of the sun; and allowed for this in his calculations by supposing that the centre, about which the sun moves uniformly, is situated a little distance from the fixed earth. He called this point the _excentric_. The line from the earth to the "excentric" was called the _line of apses_. A circle having this centre was called the _equant_, and he supposed that a radius drawn to the sun from the excentric passes over equal arcs on the equant in equal times. He then computed tables for predicting the place of the sun.

He proceeded in the same way to compute Lunar tables. Making use of ChaldÃan eclipses, he was able to get an accurate value of the moon's mean motion. [Halley, in 1693, compared this value with his own measurements, and so discovered the acceleration of the moon's mean motion. This was conclusively established, but could not be explained by the Newtonian theory for quite a long time.] He determined the plane of the moon's orbit and its inclination to the ecliptic. The motion of this plane round the pole of the ecliptic once in eighteen years complicated the problem. He located the moon's excentric as he had done the sun's. He also discovered some of the minor irregularities of the moon's motion, due, as Newton's theory proves, to the disturbing action of the sun's attraction.

In the year 134 B.C. Hipparchus observed a new star. This upset every notion about the permanence of the fixed stars. He then set to work to catalogue all the principal stars so as to know if any others appeared or disappeared. Here his experiences resembled those of several later astronomers, who, when in search of some special object, have been rewarded by a discovery in a totally different direction. On comparing his star positions with those of Timocharis and Aristillus he round no

stars that had appeared or disappeared in the interval of 150 years; but he found that all the stars seemed to have changed their places with reference to that point in the heavens where the ecliptic is 90Â from the poles of the earth–i.e., the equinox. He found that this could be explained by a motion of the equinox in the direction of the apparent diurnal motion of the stars. This discovery of _precession of the equinoxes_, which takes place at the rate of 52".1 every year, was necessary for the progress of accurate astronomical observations. It is due to a steady revolution of the earth's pole round the pole of the ecliptic once in 26,000 years in the opposite direction to the planetary revolutions.

Hipparchus was also the inventor of trigonometry, both plane and spherical. He explained the method of using eclipses for determining the longitude.

In connection with Hipparchus' great discovery it may be mentioned that modern astronomers have often attempted to fix dates in history by the effects of precession of the equinoxes. (1) At about the date when the Great Pyramid may have been built ÎDraconis was near to the pole, and must have been used as the pole-star. In the north face of the Great Pyramid is the entrance to an inclined passage, and six of the nine pyramids at Gizeh possess the same feature; all the passages being inclined at an angle between 26Â and 27Â to the horizon and in the plane of the meridian. It also appears that 4,000 years ago–i.e., about 2100 B.C.–an observer at the lower end of the passage would be able to see ÎDraconis, the then pole-star, at its lower culmination.[1] It has been suggested that the passage was made for this purpose. On other grounds the date assigned to the Great Pyramid is 2123 B.C.

(2) The ChaldÃans gave names to constellations now invisible from Babylon which would have been visible in 2000 B.C., at which date it is claimed that these people were studying astronomy.

(3) In the Odyssey, Calypso directs Odysseus, in accordance with Phoenician rules for navigating the Mediterranean, to keep the Great Bear "ever on the left as he traversed the deep" when sailing from the pillars of Hercules (Gibraltar) to Corfu. Yet such a course taken now would land the traveller in Africa. Odysseus is said in his voyage in springtime to have seen the Pleiades and Arcturus setting late, which seemed to early commentators a proof of Homer's inaccuracy. Likewise Homer, both in the _Odyssey_ [2] (v. 272-5) and in the _Iliad_ (xviii. 489), asserts that the Great Bear never set in those latitudes. Now it has been found that the precession of the equinoxes explains all these puzzles; shows that in springtime on the Mediterranean the Bear was just above the horizon, near the sea but not touching it, between 750 B.C. and 1000 B.C.; and fixes the date of the poems, thus confirming other evidence, and establishing Homer's character for accuracy. [3]

(4) The orientation of Egyptian temples and Druidical stones is such that possibly they were so placed as to assist in the observation of the heliacal risings [4] of certain stars. If the star were known, this would give an approximate date. Up to the present the results of these investigations are far from being conclusive.

Ptolemy (130 A.D.) wrote the Suntaxis, or Almagest, which includes a cyclopedia of astronomy, containing a summary of knowledge at that date. We have no evidence beyond his own statement that he was a practical observer. He theorised on the planetary motions, and held that the earth is fixed in the centre of the universe. He adopted the excentric and equant of Hipparchus to explain the unequal motions of the sun and moon. He adopted the epicycles and deferents which had been used by Apollonius and others to explain the retrograde motions of the planets. We, who know that the earth revolves round the sun once in a year, can understand that the apparent motion of a planet is only its motion relative to the earth. If, then, we suppose the earth fixed and the sun to revolve round it once a year, and the planets each in its own period, it is only necessary to impose upon each of these an additional _annual_ motion to enable us to represent truly the apparent motions. This way of looking at the apparent motions shows why each planet, when nearest to the earth, seems to move for a time in a retrograde direction. The attempts of Ptolemy and others of his time to explain the retrograde motion in this way were only approximate. Let us suppose each planet to have a bar with one end centred at the earth. If at the other end of the bar one end of a shorter bar is pivotted, having the planet at its other end, then the planet is given an annual motion in the secondary circle (the epicycle), whose centre revolves round the earth on the primary circle (the _deferent_), at a uniform rate round the excentric. Ptolemy supposed the centres of the epicycles of Mercury and Venus to be on a bar passing through the sun, and to be between the earth and the sun. The centres of the epicycles of Mars, Jupiter, and Saturn were supposed to be further away than the sun. Mercury and Venus were supposed to revolve in their epicycles in their own periodic times and in the deferent round the earth in a year. The major planets were supposed to revolve in the deferent round the earth in their own periodic times, and in their epicycles once in a year.

It did not occur to Ptolemy to place the centres of the epicycles of Mercury and Venus at the sun, and to extend the same system to the major planets. Something of this sort had been proposed by the Egyptians (we are told by Cicero and others), and was accepted by Tycho Brahe; and was as true a representation of the relative motions in the solar system as when we suppose the sun to be fixed and the earth to revolve.

The cumbrous system advocated by Ptolemy answered its purpose, enabling him to predict astronomical events approximately. He improved

the lunar theory considerably, and discovered minor inequalities which could be allowed for by the addition of new epicycles. We may look upon these epicycles of Apollonius, and the excentric of Hipparchus, as the responses of these astronomers to the demand of Plato for uniform circular motions. Their use became more and more confirmed, until the seventeenth century, when the accurate observations of Tycho Brahe enabled Kepler to abolish these purely geometrical makeshifts, and to substitute a system in which the sun became physically its controller.

FOOTNOTES:

[1] _Phil. Mag_., vol. xxiv., pp. 481-4.

[2]

ÎÎÎÎÎÎÎłÏ ÏÊ ÎÌÏÎ¿ÏÏÌÎÏÎ ÎÎłÎÌ Î¿ÌÏÎÌ ÎÏÎ¿ÎÏÎł ÎÎ¿ÏÏÏÎ
ÊÎÏÎÏÎ¿Î ÎÌ, ÎÌÍÎ ÎÎłÎÌ ÎłÌÍÎÎłÎÎł ÎÌÏÎÎÎÏÎÎ ÎÎłÎÎ¿ÏÏÎÎ,
ÊÎ ÏÌ ÎłÏÌÏÎ¿ÏÌ ÏÏÏÎÏÏÎłÎ ÎÎłÎÌ ÏÌ ÊÎÏÏÎÎł ÎÎ¿ÎÎÏÎ,
ÎŸÎÌÍÎ ÎÌÎłÌÍÎÎÎ¿ÏÎ¿Ï ÎÌÏÏÎ ÎÎ¿ÎÏÏÏÎ ÊÎÎÎÎłÎÎ¿ÎÌÎ¿.

"The Pleiades and BoÃtes that setteth late, and the Bear, which they likewise call the Wain, which turneth ever in one place, and keepeth watch upon Orion, and alone hath no part in the baths of the ocean."

[3] See Pearson in the Camb. Phil. Soc. Proc., vol. iv., pt. ii., p. 93, on whose authority the above statements are made.

[4] See p. 6 for definition.

4. THE REIGN OF EPICYCLES–FROM PTOLEMY TO COPERNICUS.

After Ptolemy had published his book there seemed to be nothing more to do for the solar system except to go on observing and finding more and more accurate values for the constants involved–viz., the periods of revolution, the diameter of the deferent,[1] and its ratio to that of the epicycle,[2] the distance of the excentric[3] from the centre of the deferent, and the position of the line of apses,[4] besides the inclination and position of the plane of the planet's orbit. The only object ever aimed at in those days was to prepare tables for predicting the places of the planets. It was not a mechanical problem; there was no notion of a governing law of forces.

From this time onwards all interest in astronomy seemed, in Europe at least, to sink to a low ebb. When the Caliph Omar, in the middle of the seventh century, burnt the library of Alexandria, which had been the centre of intellectual progress, that centre migrated to Baghdad, and the Arabs became the leaders of science and philosophy. In astronomy they made careful observations. In the middle of the ninth

century Albategnius, a Syrian prince, improved the value of excentricity of the sun's orbit, observed the motion of the moon's apse, and thought he detected a smaller progression of the sun's apse. His tables were much more accurate than Ptolemy's. Abul Wefa, in the tenth century, seems to have discovered the moon's "variation." Meanwhile the Moors were leaders of science in the west, and Arzachel of Toledo improved the solar tables very much. Ulugh Begh, grandson of the great Tamerlane the Tartar, built a fine observatory at Samarcand in the fifteenth century, and made a great catalogue of stars, the first since the time of Hipparchus.

At the close of the fifteenth century King Alphonso of Spain employed computers to produce the Alphonsine Tables (1488 A.D.), Purbach translated Ptolemy's book, and observations were carried out in Germany by MÃller, known as Regiomontanus, and Waltherus.

Nicolai Copernicus, a Sclav, was born in 1473 at Thorn, in Polish Prussia. He studied at Cracow and in Italy. He was a priest, and settled at Frauenberg. He did not undertake continuous observations, but devoted himself to simplifying the planetary systems and devising means for more accurately predicting the positions of the sun, moon, and planets. He had no idea of framing a solar system on a dynamical basis. His great object was to increase the accuracy of the calculations and the tables. The results of his cogitations were printed just before his death in an interesting book, _De Revolutionibus Orbium Celestium_. It is only by careful reading of this book that the true position of Copernicus can be realised. He noticed that Nicetas and others had ascribed the apparent diurnal rotation of the heavens to a real daily rotation of the earth about its axis, in the opposite direction to the apparent motion of the stars. Also in the writings of Martianus Capella he learnt that the Egyptians had supposed Mercury and Venus to revolve round the sun, and to be carried with him in his annual motion round the earth. He noticed that the same supposition, if extended to Mars, Jupiter, and Saturn, would explain easily why they, and especially Mars, seem so much brighter in opposition. For Mars would then be a great deal nearer to the earth than at other times. It would also explain the retrograde motion of planets when in opposition.

We must here notice that at this stage Copernicus was actually confronted with the system accepted later by Tycho Brahe, with the earth fixed. But he now recalled and accepted the views of Pythagoras and others, according to which the sun is fixed and the earth revolves; and it must be noted that, geometrically, there is no difference of any sort between the Egyptian or Tychonic system and that of Pythagoras as revived by Copernicus, except that on the latter theory the stars ought to seem to move when the earth changes its position–a test which failed completely with the rough means of observation then available. The radical defect of all solar systems previous to the time of Kepler (1609 A.D.) was the slavish yielding to

Plato's dictum demanding uniform circular motion for the planets, and the consequent evolution of the epicycle, which was fatal to any conception of a dynamical theory.

Copernicus could not sever himself from this obnoxious tradition.[5] It is true that neither the Pythagorean nor the Egypto-Tychonic system required epicycles for explaining retrograde motion, as the Ptolemaic theory did. Furthermore, either system could use the excentric of Hipparchus to explain the irregular motion known as the equation of the centre. But Copernicus remarked that he could also use an epicycle for this purpose, or that he could use both an excentric and an epicycle for each planet, and so bring theory still closer into accord with observation. And this he proceeded to do.[6] Moreover, observers had found irregularities in the moon's motion, due, as we now know, to the disturbing attraction of the sun. To correct for these irregularities Copernicus introduced epicycle on epicycle in the lunar orbit.

This is in its main features the system propounded by Copernicus. But attention must, to state the case fully, be drawn to two points to be found in his first and sixth books respectively. The first point relates to the seasons, and it shows a strange ignorance of the laws of rotating bodies. To use the words of Delambre,[7] in drawing attention to the strange conception,

he imagined that the earth, revolving round the sun, ought always to show to it the same face; the contrary phenomena surprised him: to explain them he invented a third motion, and added it to the two real motions (rotation and orbital revolution). By this third motion the earth, he held, made a revolution on itself and on the poles of the ecliptic once a year ... Copernicus did not know that motion in a straight line is the natural motion, and that motion in a curve is the resultant of several movements. He believed, with Aristotle, that circular motion was the natural one.

Copernicus made this rotation of the earth's axis about the pole of the ecliptic retrograde (i.e., opposite to the orbital revolution), and by making it perform more than one complete revolution in a year, the added part being 1/26000 of the whole, he was able to include the precession of the equinoxes in his explanation of the seasons. His explanation of the seasons is given on leaf 10 of his book (the pages of this book are not all numbered, only alternate pages, or leaves).

In his sixth book he discusses the inclination of the planetary orbits to the ecliptic. In regard to this the theory of Copernicus is unique; and it will be best to explain this in the words of Grant in his great work.[8] He says:–

Copernicus, as we have already remarked, did not attack the principle of the epicyclical theory: he merely sought to make it

more simple by placing the centre of the earth's orbit in the centre of the universe. This was the point to which the motions of the planets were referred, for the planes of their orbits were made to pass through it, and their points of least and greatest velocities were also determined with reference to it. By this arrangement the sun was situate mathematically near the centre of the planetary system, but he did not appear to have any physical connexion with the planets as the centre of their motions.

According to Copernicus' sixth book, the planes of the planetary orbits do not pass through the sun, and the lines of apses do not pass through to the sun.

Such was the theory advanced by Copernicus: The earth moves in an epicycle, on a deferent whose centre is a little distance from the sun. The planets move in a similar way on epicycles, but their deferents have no geometrical or physical relation to the sun. The moon moves on an epicycle centred on a second epicycle, itself centred on a deferent, excentric to the earth. The earth's axis rotates about the pole of the ecliptic, making one revolution and a twenty-six thousandth part of a revolution in the sidereal year, in the opposite direction to its orbital motion.

In view of this fanciful structure it must be noted, in fairness to Copernicus, that he repeatedly states that the reader is not obliged to accept his system as showing the real motions; that it does not matter whether they be true, even approximately, or not, so long as they enable us to compute tables from which the places of the planets among the stars can be predicted.[9] He says that whoever is not satisfied with this explanation must be contented by being told that "mathematics are for mathematicians" (Mathematicis mathematica scribuntur).

At the same time he expresses his conviction over and over again that the earth is in motion. It is with him a pious belief, just as it was with Pythagoras and his school and with Aristarchus. "But" (as Dreyer says in his most interesting book, _Tycho Brahe_) "proofs of the physical truth of his system Copernicus had given none, and could give none," any more than Pythagoras or Aristarchus.

There was nothing so startlingly simple in his system as to lead the cautious astronomer to accept it, as there was in the later Keplerian system; and the absence of parallax in the stars seemed to condemn his system, which had no physical basis to recommend it, and no simplification at all over the Egypto-Tychonic system, to which Copernicus himself drew attention. It has been necessary to devote perhaps undue space to the interesting work of Copernicus, because by a curious chance his name has become so widely known. He has been spoken of very generally as the founder of the solar system that is now accepted. This seems unfair, and on reading over what has been

written about him at different times it will be noticed that the astronomers–those who have evidently read his great book–are very cautious in the words with which they eulogise him, and refrain from attributing to him the foundation of our solar system, which is entirely due to Kepler. It is only the more popular writers who give the idea that a revolution had been effected when Pythagoras' system was revived, and when Copernicus supported his view that the earth moves and is not fixed.

It may be easy to explain the association of the name of Copernicus with the Keplerian system. But the time has long passed when the historian can support in any way this popular error, which was started not by astronomers acquainted with Kepler's work, but by those who desired to put the Church in the wrong by extolling Copernicus.

Copernicus dreaded much the abuse he expected to receive from philosophers for opposing the authority of Aristotle, who had declared that the earth was fixed. So he sought and obtained the support of the Church, dedicating his great work to Pope Paul III. in a lengthy explanatory epistle. The Bishop of Cracow set up a memorial tablet in his honour.

Copernicus was the most refined exponent, and almost the last representative, of the Epicyclical School. As has been already stated, his successor, Tycho Brahe, supported the same use of epicycles and excentrics as Copernicus, though he held the earth to be fixed. But Tycho Brahe was eminently a practical observer, and took little part in theory; and his observations formed so essential a portion of the system of Kepler that it is only fair to include his name among these who laid the foundations of the solar system which we accept to-day.

In now taking leave of the system of epicycles let it be remarked that it has been held up to ridicule more than it deserves. On reading Airy's account of epicycles, in the beautifully clear language of his _Six Lectures on Astronomy_, the impression is made that the jointed bars there spoken of for describing the circles were supposed to be real. This is no more the case than that the spheres of Eudoxus and Callippus were supposed to be real. Both were introduced only to illustrate the mathematical conception upon which the solar, planetary, and lunar tables were constructed. The epicycles represented nothing more nor less than the first terms in the Fourier series, which in the last century has become a basis of such calculations, both in astronomy and physics generally.

[Illustration: "QUADRANS MURALIS SIVE TICHONICUS." With portrait of
Tycho Brahe, instruments, etc., painted on the wall; showing
assistants using the sight, watching the clock, and recording. (From
the author's copy of the _AstronomiÃ InstauratÃ Mechanica._)]

FOOTNOTES:

[1] For definition see p. 22.

[2] _Ibid_.

[3] For definition see p. 18.

[4] For definition see p. 18.

[5] In his great book Copernicus says: "The movement of the heavenly bodies is uniform, circular, perpetual, or else composed of circular movements." In this he proclaimed himself a follower of Pythagoras (see p. 14), as also when he says: "The world is spherical because the sphere is, of all figures, the most perfect" (Delambre, _Ast. Mod. Hist_., pp. 86, 87).

[6] Kepler tells us that Tycho Brahe was pleased with this device, and adapted it to his own system.

[7] _Hist. Ast._, vol. i., p. 354.

[8] _Hist. of Phys. Ast._, p. vii.

[9] "Est enim Astronomi proprium, historiam motuum coelestium diligenti et artificiosa observatione colligere. Deinde causas earundem, seu hypotheses, cum veras assequi nulla ratione possit ... Neque enim necesse est, eas hypotheses esse veras, imo ne verisimiles quidem, sed sufficit hoc usum, si calculum observationibus congruentem exhibeant."

BOOK II. THE DYNAMICAL PERIOD

5. DISCOVERY OF THE TRUE SOLAR SYSTEM–TYCHO BRAHE–KEPLER.

During the period of the intellectual and aesthetic revival, at the beginning of the sixteenth century, the "spirit of the age" was fostered by the invention of printing, by the downfall of the Byzantine Empire, and the scattering of Greek fugitives, carrying the treasures of literature through Western Europe, by the works of Raphael and Michael Angelo, by the Reformation, and by the extension of the known world through the voyages of Spaniards and Portuguese. During that period there came to the front the founder of accurate observational astronomy. Tycho Brahe, a Dane, born in 1546 of noble parents, was the most distinguished, diligent, and accurate observer of the heavens since the days of Hipparchus, 1,700 years before.

Tycho was devoted entirely to his science from childhood, and the opposition of his parents only stimulated him in his efforts to overcome difficulties. He soon grasped the hopelessness of the old deductive methods of reasoning, and decided that no theories ought to be indulged in until preparations had been made by the accumulation of accurate observations. We may claim for him the title of founder of the inductive method.

For a complete life of this great man the reader is referred to Dreyer's _Tycho Brahe_, Edinburgh, 1890, containing a complete bibliography. The present notice must be limited to noting the work done, and the qualities of character which enabled him to attain his scientific aims, and which have been conspicuous in many of his successors.

He studied in Germany, but King Frederick of Denmark, appreciating his great talents, invited him to carry out his life's work in that country. He granted to him the island of Hveen, gave him a pension, and made him a canon of the Cathedral of Roskilde. On that island Tycho Brahe built the splendid observatory which he called Uraniborg, and, later, a second one for his assistants and students, called Stjerneborg. These he fitted up with the most perfect instruments, and never lost a chance of adding to his stock of careful observations.[1]

The account of all these instruments and observations, printed at his own press on the island, was published by Tycho Brahe himself, and the admirable and numerous engravings bear witness to the excellence of design and the stability of his instruments.

His mechanical skill was very great, and in his workmanship he was satisfied with nothing but the best. He recognised the importance of rigidity in the instruments, and, whereas these had generally been made of wood, he designed them in metal. His instruments included armillae like those which had been used in Alexandria, and other armillae designed by himself–sextants, mural quadrants, large celestial globes and various instruments for special purposes. He lived before the days of telescopes and accurate clocks. He invented the method of sub-dividing the degrees on the arc of an instrument by transversals somewhat in the way that Pedro Nunez had proposed.

He originated the true system of observation and reduction of observations, recognising the fact that the best instrument in the world is not perfect; and with each of his instruments he set to work to find out the errors of graduation and the errors of mounting, the necessary correction being applied to each observation.

When he wanted to point his instrument exactly to a star he was confronted with precisely the same difficulty as is met in gunnery and rifle-shooting. The sights and the object aimed at cannot be in focus together, and a great deal depends on the form of sight. Tycho Brahe

invented, and applied to the pointers of his instruments, an aperture-sight of variable area, like the iris diaphragm used now in photography. This enabled him to get the best result with stars of different brightness. The telescope not having been invented, he could not use a telescopic-sight as we now do in gunnery. This not only removes the difficulty of focussing, but makes the minimum visible angle smaller. Helmholtz has defined the minimum angle measurable with the naked eye as being one minute of arc. In view of this it is simply marvellous that, when the positions of Tycho's standard stars are compared with the best modern catalogues, his probable error in right ascension is only Âł 24", 1, and in declination only Âł 25", 9.

Clocks of a sort had been made, but Tycho Brahe found them so unreliable that he seldom used them, and many of his position-measurements were made by measuring the angular distances from known stars.

Taking into consideration the absence of either a telescope or a clock, and reading his account of the labour he bestowed upon each observation, we must all agree that Kepler, who inherited these observations in MS., was justified, under the conditions then existing, in declaring that there was no hope of anyone ever improving upon them.

In the year 1572, on November 11th, Tycho discovered in Cassiopeia a new star of great brilliance, and continued to observe it until the end of January, 1573. So incredible to him was such an event that he refused to believe his own eyes until he got others to confirm what he saw. He made accurate observations of its distance from the nine principal stars in Casseiopeia, and proved that it had no measurable parallax. Later he employed the same method with the comets of 1577, 1580, 1582, 1585, 1590, 1593, and 1596, and proved that they too had no measurable parallax and must be very distant.

The startling discovery that stars are not necessarily permanent, that new stars may appear, and possibly that old ones may disappear, had upon him exactly the same effect that a similar occurrence had upon Hipparchus 1,700 years before. He felt it his duty to catalogue all the principal stars, so that there should be no mistake in the future. During the construction of his catalogue of 1,000 stars he prepared and used accurate tables of refraction deduced from his own observations. Thus he eliminated (so far as naked eye observations required) the effect of atmospheric refraction which makes the altitude of a star seem greater than it really is.

Tycho Brahe was able to correct the lunar theory by his observations. Copernicus had introduced two epicycles on the lunar orbit in the hope of obtaining a better accordance between theory and observation; and he was not too ambitious, as his desire was to get the tables accurate to ten minutes. Tycho Brahe found that the tables of Copernicus were

in error as much as two degrees. He re-discovered the inequality called "variation" by observing the moon in all phases–a thing which had not been attended to. [It is remarkable that in the nineteenth century Sir George Airy established an altazimuth at Greenwich Observatory with this special object, to get observations of the moon in all phases.] He also discovered other lunar equalities, and wanted to add another epicycle to the moon's orbit, but he feared that these would soon become unmanageable if further observations showed more new inequalities.

But, as it turned out, the most fruitful work of Tycho Brahe was on the motions of the planets, and especially of the planet Mars, for it was by an examination of these results that Kepler was led to the discovery of his immortal laws.

After the death of King Frederick the observatories of Tycho Brahe were not supported. The gigantic power and industry displayed by this determined man were accompanied, as often happens, by an overbearing manner, intolerant of obstacles. This led to friction, and eventually the observatories were dismantled, and Tycho Brahe was received by the Emperor Rudolph II., who placed a house in Prague at his disposal. Here he worked for a few years, with Kepler as one of his assistants, and he died in the year 1601.

It is an interesting fact that Tycho Brahe had a firm conviction that mundane events could be predicted by astrology, and that this belief was supported by his own predictions.

It has already been stated that Tycho Brahe maintained that observation must precede theory. He did not accept the Copernican theory that the earth moves, but for a working hypothesis he used a modification of an old Egyptian theory, mathematically identical with that of Copernicus, but not involving a stellar parallax. He says (_De Mundi_, etc.) that

the Ptolemean system was too complicated, and the new one which that great man Copernicus had proposed, following in the footsteps of Aristarchus of Samos, though there was nothing in it contrary to mathematical principles, was in opposition to those of physics, as the heavy and sluggish earth is unfit to move, and the system is even opposed to the authority of Scripture. The absence of annual parallax further involves an incredible distance between the outermost planet and the fixed stars.

We are bound to admit that in the circumstances of the case, so long as there was no question of dynamical forces connecting the members of the solar system, his reasoning, as we should expect from such a man, is practical and sound. It is not surprising, then, that astronomers generally did not readily accept the views of Copernicus, that Luther (Luther's _Tischreden_, pp. 22, 60) derided him in his usual pithy

manner, that Melancthon (_Initia doctrinae physicae_) said that Scripture, and also science, are against the earth's motion; and that the men of science whose opinion was asked for by the cardinals (who wished to know whether Galileo was right or wrong) looked upon Copernicus as a weaver of fanciful theories.

Johann Kepler is the name of the man whose place, as is generally agreed, would have been the most difficult to fill among all those who have contributed to the advance of astronomical knowledge. He was born at Wiel, in the Duchy of Wurtemberg, in 1571. He held an appointment at Gratz, in Styria, and went to join Tycho Brahe in Prague, and to assist in reducing his observations. These came into his possession when Tycho Brahe died, the Emperor Rudolph entrusting to him the preparation of new tables (called the Rudolphine tables) founded on the new and accurate observations. He had the most profound respect for the knowledge, skill, determination, and perseverance of the man who had reaped such a harvest of most accurate data; and though Tycho hardly recognised the transcendent genius of the man who was working as his assistant, and although there were disagreements between them, Kepler held to his post, sustained by the conviction that, with these observations to test any theory, he would be in a position to settle for ever the problem of the solar system.

[Illustration: PORTRAIT OF JOHANNES KEPLER. By F. Wanderer, from Reitlinger's "Johannes Kepler" (original in Strassburg).]

It has seemed to many that Plato's demand for uniform circular motion (linear or angular) was responsible for a loss to astronomy of good work during fifteen hundred years, for a hundred ill-considered speculative cosmogonies, for dissatisfaction, amounting to disgust, with these _Ã priori_ guesses, and for the relegation of the science to less intellectual races than Greeks and other Europeans. Nobody seemed to dare to depart from this fetish of uniform angular motion and circular orbits until the insight, boldness, and independence of Johann Kepler opened up a new world of thought and of intellectual delight.

While at work on the Rudolphine tables he used the old epicycles and deferents and excentrics, but he could not make theory agree with observation. His instincts told him that these apologists for uniform motion were a fraud; and he proved it to himself by trying every possible variation of the elements and finding them fail. The number of hypotheses which he examined and rejected was almost incredible (for example, that the planets turn round centres at a little distance from the sun, that the epicycles have centres at a little distance from the deferent, and so on). He says that, after using all these devices to make theory agree with Tycho's observations, he still found errors amounting to eight minutes of a degree. Then he said boldly that it was impossible that so good an observer as Tycho could have made a mistake of eight minutes, and added: "Out of these eight

minutes we will construct a new theory that will explain the motions of all the planets." And he did it, with elliptic orbits having the sun in a focus of each.[2]

It is often difficult to define the boundaries between fancies, imagination, hypothesis, and sound theory. This extraordinary genius was a master in all these modes of attacking a problem. His analogy between the spaces occupied by the five regular solids and the distances of the planets from the sun, which filled him with so much delight, was a display of pure fancy. His demonstration of the three fundamental laws of planetary motion was the most strict and complete theory that had ever been attempted.

It has been often suggested that the revival by Copernicus of the notion of a moving earth was a help to Kepler. No one who reads Kepler's great book could hold such an opinion for a moment. In fact, the excellence of Copernicus's book helped to prolong the life of the epicyclical theories in opposition to Kepler's teaching.

All of the best theories were compared by him with observation. These were the Ptolemaic, the Copernican, and the Tychonic. The two latter placed all of the planetary orbits concentric with one another, the sun being placed a little away from their common centre, and having no apparent relation to them, and being actually outside the planes in which they move. Kepler's first great discovery was that the planes of all the orbits pass through the sun; his second was that the line of apses of each planet passes through the sun; both were contradictory to the Copernican theory.

He proceeds cautiously with his propositions until he arrives at his great laws, and he concludes his book by comparing observations of Mars, of all dates, with his theory.

His first law states that the planets describe ellipses with the sun at a focus of each ellipse.

His second law (a far more difficult one to prove) states that a line drawn from a planet to the sun sweeps over equal areas in equal times. These two laws were published in his great work, _Astronomia Nova, sen. Physica Coelestis tradita commentariis de Motibus Stelloe; Martis_, Prague, 1609.

It took him nine years more[3] to discover his third law, that the squares of the periodic times are proportional to the cubes of the mean distances from the sun.

These three laws contain implicitly the law of universal gravitation. They are simply an alternative way of expressing that law in dealing with planets, not particles. Only, the power of the greatest human intellect is so utterly feeble that the meaning of the

words in Kepler's three laws could not be understood until expounded by the logic of Newton's dynamics.

The joy with which Kepler contemplated the final demonstration of these laws, the evolution of which had occupied twenty years, can hardly be imagined by us. He has given some idea of it in a passage in his work on _Harmonics_, which is not now quoted, only lest someone might say it was egotistical–a term which is simply grotesque when applied to such a man with such a life's work accomplished.

The whole book, _Astronomia Nova_, is a pleasure to read; the mass of observations that are used, and the ingenuity of the propositions, contrast strongly with the loose and imperfectly supported explanations of all his predecessors; and the indulgent reader will excuse the devotion of a few lines to an example of the ingenuity and beauty of his methods.

It may seem a hopeless task to find out the true paths of Mars and the earth (at that time when their shape even was not known) from the observations giving only the relative direction from night to night. Now, Kepler had twenty years of observations of Mars to deal with. This enabled him to use a new method, to find the earth's orbit. Observe the date at any time when Mars is in opposition. The earth's position E at that date gives the longitude of Mars M. His period is 687 days. Now choose dates before and after the principal date at intervals of 687 days and its multiples. Mars is in each case in the same position. Now for any date when Mars is at M and the earth at Eâ the date of the year gives the angle EâSM. And the observation of Tycho gives the direction of Mars compared with the sun, SEâM. So all the angles of the triangle SEM in any of these positions of E are known, and also the ratios of SEâ, SEâ, SEâ, SEâ to SM and to each other.

For the orbit of Mars observations were chosen at intervals of a year, when the earth was always in the same place.

[Illustration]

But Kepler saw much farther than the geometrical facts. He realised that the orbits are followed owing to a force directed to the sun; and he guessed that this is the same force as the gravity that makes a stone fall. He saw the difficulty of gravitation acting through the void space. He compared universal gravitation to magnetism, and speaks of the work of Gilbert of Colchester. (Gilbert's book, _De Mundo Nostro Sublunari, Philosophia Nova_, Amstelodami, 1651, containing similar views, was published forty-eight years after Gilbert's death, and forty-two years after Kepler's book and reference. His book _De Magnete_ was published in 1600.)

A few of Kepler's views on gravitation, extracted from the

Introduction to his _Astronomia Nova_, may now be mentioned:–

1. Every body at rest remains at rest if outside the attractive power of other bodies.

2. Gravity is a property of masses mutually attracting in such manner that the earth attracts a stone much more than a stone attracts the earth.

3. Bodies are attracted to the earth's centre, not because it is the centre of the universe, but because it is the centre of the attracting particles of the earth.

4. If the earth be not round (but spheroidal?), then bodies at different latitudes will not be attracted to its centre, but to different points in the neighbourhood of that centre.

5. If the earth and moon were not retained in their orbits by vital force (_aut alia aligua aequipollenti_), the earth and moon would come together.

6. If the earth were to cease to attract its waters, the oceans would all rise and flow to the moon.

7. He attributes the tides to lunar attraction. Kepler had been appointed Imperial Astronomer with a handsome salary (on paper), a fraction of which was doled out to him very irregularly. He was led to miserable makeshifts to earn enough to keep his family from starvation; and proceeded to Ratisbon in 1630 to represent his claims to the Diet. He arrived worn out and debilitated; he failed in his appeal, and died from fever, contracted under, and fed upon, disappointment and exhaustion. Those were not the days when men could adopt as a profession the "research of endowment."

Before taking leave of Kepler, who was by no means a man of one idea, it ought to be here recorded that he was the first to suggest that a telescope made with both lenses convex (not a Galilean telescope) can have cross wires in the focus, for use as a pointer to fix accurately the positions of stars. An Englishman, Gascoigne, was the first to use this in practice.

From the all too brief epitome here given of Kepler's greatest book, it must be obvious that he had at that time some inkling of the meaning of his laws–universal gravitation. From that moment the idea

of universal gravitation was in the air, and hints and guesses were thrown out by many; and in time the law of gravitation would doubtless have been discovered, though probably not by the work of one man, even if Newton had not lived. But, if Kepler had not lived, who else could have discovered his laws?

FOOTNOTES:

[1] When the writer visited M. D'Arrest, the astronomer, at Copenhagen, in 1872, he was presented by D'Arrest with one of several bricks collected from the ruins of Uraniborg. This was one of his most cherished possessions until, on returning home after a prolonged absence on astronomical work, he found that his treasure had been tidied away from his study.

[2] An ellipse is one of the plane, sections of a cone. It is an oval curve, which may be drawn by fixing two pins in a sheet of paper at S and H, fastening a string, SPH, to the two pins, and stretching it with a pencil point at P, and moving the pencil point, while the string is kept taut, to trace the oval ellipse, APB. S and H are the _foci_. Kepler found the sun to be in one focus, say S. AB is the _major axis_. DE is the _minor axis_. C is the _centre_. The direction of AB is the _line of apses_. The ratio of CS to CA is the _excentricity_. The position of the planet at A is the _perihelion_ (nearest to the sun). The position of the planet at B is the _aphelion_ (farthest from the sun). The angle ASP is the _anomaly_ when the planet is at P. CA or a line drawn from S to D is the _mean distance_ of the planet from the sun.

[Illustration]

[3] The ruled logarithmic paper we now use was not then to be had by going into a stationer's shop. Else he would have accomplished this in five minutes.

6. GALILEO AND THE TELESCOPE–NOTIONS OF GRAVITY BY HORROCKS, ETC.

It is now necessary to leave the subject of dynamical astronomy for a short time in order to give some account of work in a different direction originated by a contemporary of Kepler's, his senior in fact by seven years. Galileo Galilei was born at Pisa in 1564. The most scientific part of his work dealt with terrestrial dynamics; but one of those fortunate chances which happen only to really great men put him in the way of originating a new branch of astronomy.

The laws of motion had not been correctly defined. The only man of Galileo's time who seems to have worked successfully in the same direction as himself was that Admirable Crichton of the Italians, Leonardo da Vinci. Galileo cleared the ground. It had always been

noticed that things tend to come to rest; a ball rolled on the ground, a boat moved on the water, a shot fired in the air. Galileo realised that in all of these cases a resisting force acts to stop the motion, and he was the first to arrive at the not very obvious law that the motion of a body will never stop, nor vary its speed, nor change its direction, except by the action of some force.

It is not very obvious that a light body and a heavy one fall at the same speed (except for the resistance of the air). Galileo proved this on paper, but to convince the world he had to experiment from the leaning tower of Pisa.

At an early age he discovered the principle of isochronism of the pendulum, which, in the hands of Huyghens in the middle of the seventeenth century, led to the invention of the pendulum clock, perhaps the most valuable astronomical instrument ever produced.

These and other discoveries in dynamics may seem very obvious now; but it is often the most every-day matters which have been found to elude the inquiries of ordinary minds, and it required a high order of intellect to unravel the truth and discard the stupid maxims scattered through the works of Aristotle and accepted on his authority. A blind worship of scientific authorities has often delayed the progress of human knowledge, just as too much "instruction" of a youth often ruins his "education." Grant, in his history of Physical Astronomy, has well said that "the sagacity and skill which Galileo displays in resolving the phenomena of motion into their constituent elements, and hence deriving the original principles involved in them, will ever assure to him a distinguished place among those who have extended the domains of science."

But it was work of a different kind that established Galileo's popular reputation. In 1609 Galileo heard that a Dutch spectacle-maker had combined a pair of lenses so as to magnify distant objects. Working on this hint, he solved the same problem, first on paper and then in practice. So he came to make one of the first telescopes ever used in astronomy. No sooner had he turned it on the heavenly bodies than he was rewarded by such a shower of startling discoveries as forthwith made his name the best known in Europe. He found curious irregular black spots on the sun, revolving round it in twenty-seven days; hills and valleys on the moon; the planets showing discs of sensible size, not points like the fixed stars; Venus showing phases according to her position in relation to the sun; Jupiter accompanied by four moons; Saturn with appendages that he could not explain, but unlike the other planets; the Milky Way composed of a multitude of separate stars.

His fame flew over Europe like magic, and his discoveries were much discussed–and there were many who refused to believe. Cosmo de Medici induced him to migrate to Florence to carry on his observations. He was received by Paul V., the Pope, at Rome, to whom he explained his

discoveries.

He thought that these discoveries proved the truth of the Copernican theory of the Earth's motion; and he urged this view on friends and foes alike. Although in frequent correspondence with Kepler, he never alluded to the New Astronomy, and wrote to him extolling the virtue of epicycles. He loved to argue, never shirked an encounter with any number of disputants, and laughed as he broke down their arguments.

Through some strange course of events, not easy to follow, the Copernican theory, whose birth was welcomed by the Church, had now been taken up by certain anti-clerical agitators, and was opposed by the cardinals as well as by the dignitaries of the Reformed Church. Galileo–a good Catholic–got mixed up in these discussions, although on excellent terms with the Pope and his entourage. At last it came about that Galileo was summoned to appear at Rome, where he was charged with holding and teaching heretical opinions about the movement of the earth; and he then solemnly abjured these opinions. There has been much exaggeration and misstatement about his trial and punishment, and for a long time there was a great deal of bitterness shown on both sides. But the general verdict of the present day seems to be that, although Galileo himself was treated with consideration, the hostility of the Church to the views of Copernicus placed it in opposition also to the true Keplerian system, and this led to unprofitable controversies. From the time of Galileo onwards, for some time, opponents of religion included the theory of the Earth's motion in their disputations, not so much for the love, or knowledge, of astronomy, as for the pleasure of putting the Church in the wrong. This created a great deal of bitterness and intolerance on both sides. Among the sufferers was Giordano Bruno, a learned speculative philosopher, who was condemned to be burnt at the stake.

Galileo died on Christmas Day, 1642–the day of Newton's birth. The further consideration of the grand field of discovery opened out by Galileo with his telescopes must be now postponed, to avoid discontinuity in the history of the intellectual development of this period, which lay in the direction of dynamical, or physical, astronomy.

Until the time of Kepler no one seems to have conceived the idea of universal physical forces controlling terrestrial phenomena, and equally applicable to the heavenly bodies. The grand discovery by Kepler of the true relationship of the Sun to the Planets, and the telescopic discoveries of Galileo and of those who followed him, spread a spirit of inquiry and philosophic thought throughout Europe, and once more did astronomy rise in estimation; and the irresistible logic of its mathematical process of reasoning soon placed it in the position it has ever since occupied as the foremost of the exact sciences.

The practical application of this process of reasoning was enormously facilitated by the invention of logarithms by Napier. He was born at Merchistoun, near Edinburgh, in 1550, and died in 1617. By this system the tedious arithmetical operations necessary in astronomical calculations, especially those dealing with the trigonometrical functions of angles, were so much simplified that Laplace declared that by this invention the life-work of an astronomer was doubled.

Jeremiah Horrocks (born 1619, died 1641) was an ardent admirer of Tycho Brahe and Kepler, and was able to improve the Rudolphine tables so much that he foretold a transit of Venus, in 1639, which these tables failed to indicate, and was the only observer of it. His life was short, but he accomplished a great deal, and rightly ascribed the lunar inequality called _evection_ to variations in the value of the eccentricity and in the direction of the line of apses, at the same time correctly assigning _the disturbing force of the Sun_ as the cause. He discovered the errors in Jupiter's calculated place, due to what we now know as the long inequality of Jupiter and Saturn, and measured with considerable accuracy the acceleration at that date of Jupiter's mean motion, and indicated the retardation of Saturn's mean motion.

Horrocks' investigations, so far as they could be collected, were published posthumously in 1672, and seldom, if ever, has a man who lived only twenty-two years originated so much scientific knowledge.

At this period British science received a lasting impetus by the wise initiation of a much-abused man, Charles II., who founded the Royal Society of London, and also the Royal Observatory of Greeenwich, where he established Flamsteed as first Astronomer Royal, especially for lunar and stellar observations likely to be useful for navigation. At the same time the French Academy and the Paris Observatory were founded. All this within fourteen years, 1662-1675.

Meanwhile gravitation in general terms was being discussed by Hooke, Wren, Halley, and many others. All of these men felt a repugnance to accept the idea of a force acting across the empty void of space. Descartes (1596-1650) proposed an ethereal medium whirling round the sun with the planets, and having local whirls revolving with the satellites. As Delambre and Grant have said, this fiction only retarded the progress of pure science. It had no sort of relation to the more modern, but equally misleading, "nebular hypothesis." While many were talking and guessing, a giant mind was needed at this stage to make things clear.

7. SIR ISAAC NEWTON–LAW OF UNIVERSAL GRAVITATION.

We now reach the period which is the culminating point of interest in the history of dynamical astronomy. Isaac Newton was born in 1642. Pemberton states that Newton, having quitted Cambridge to avoid

the plague, was residing at Wolsthorpe, in Lincolnshire, where he had been born; that he was sitting one day in the garden, reflecting upon the force which prevents a planet from flying off at a tangent and which draws it to the sun, and upon the force which draws the moon to the earth; and that he saw in the case of the planets that the sun's force must clearly be unequal at different distances, for the pull out of the tangential line in a minute is less for Jupiter than for Mars. He then saw that the pull of the earth on the moon would be less than for a nearer object. It is said that while thus meditating he saw an apple fall from a tree to the ground, and that this fact suggested the questions: Is the force that pulled that apple from the tree the same as the force which draws the moon to the earth? Does the attraction for both of them follow the same law as to distance as is given by the planetary motions round the sun? It has been stated that in this way the first conception of universal gravitation arose.[1]

Quite the most important event in the whole history of physical astronomy was the publication, in 1687, of Newton's _Principia (Philosophiae Naturalis Principia Mathematica)_. In this great work Newton started from the beginning of things, the laws of motion, and carried his argument, step by step, into every branch of physical astronomy; giving the physical meaning of Kepler's three laws, and explaining, or indicating the explanation of, all the known heavenly motions and their irregularities; showing that all of these were included in his simple statement about the law of universal gravitation; and proceeding to deduce from that law new irregularities in the motions of the moon which had never been noticed, and to discover the oblate figure of the earth and the cause of the tides. These investigations occupied the best part of his life; but he wrote the whole of his great book in fifteen months.

Having developed and enunciated the true laws of motion, he was able to show that Kepler's second law (that equal areas are described by the line from the planet to the sun in equal times) was only another way of saying that the centripetal force on a planet is always directed to the sun. Also that Kepler's first law (elliptic orbits with the sun in one focus) was only another way of saying that the force urging a planet to the sun varies inversely as the square of the distance. Also (if these two be granted) it follows that Kepler's third law is only another way of saying that the sun's force on different planets (besides depending as above on distance) is proportional to their masses.

Having further proved the, for that day, wonderful proposition that, with the law of inverse squares, the attraction by the separate particles of a sphere of uniform density (or one composed of concentric spherical shells, each of uniform density) acts as if the whole mass were collected at the centre, he was able to express the meaning of Kepler's laws in propositions which have been summarised as follows:–

The law of universal gravitation.–_Every particle of matter in the universe attracts every other particle with a force varying inversely as the square of the distance between them, and directly as the product of the masses of the two particles_.[2]

But Newton did not commit himself to the law until he had answered that question about the apple; and the above proposition now enabled him to deal with the Moon and the apple. Gravity makes a stone fall 16.1 feet in a second. The moon is 60 times farther from the earth's centre than the stone, so it ought to be drawn out of a straight course through 16.1 feet in a minute. Newton found the distance through which she is actually drawn as a fraction of the earth's diameter. But when he first examined this matter he proceeded to use a wrong diameter for the earth, and he found a serious discrepancy. This, for a time, seemed to condemn his theory, and regretfully he laid that part of his work aside. Fortunately, before Newton wrote the _Principia_ the French astronomer Picard made a new and correct measure of an arc of the meridian, from which he obtained an accurate value of the earth's diameter. Newton applied this value, and found, to his great joy, that when the distance of the moon is 60 times the radius of the earth she is attracted out of the straight course 16.1 feet per minute, and that the force acting on a stone or an apple follows the same law as the force acting upon the heavenly bodies.[3]

The universality claimed for the law–if not by Newton, at least by his commentators–was bold, and warranted only by the large number of cases in which Newton had found it to apply. Its universality has been under test ever since, and so far it has stood the test. There has often been a suspicion of a doubt, when some inequality of motion in the heavenly bodies has, for a time, foiled the astronomers in their attempts to explain it. But improved mathematical methods have always succeeded in the end, and so the seeming doubt has been converted into a surer conviction of the universality of the law.

Having once established the law, Newton proceeded to trace some of its consequences. He saw that the figure of the earth depends partly on the mutual gravitation of its parts, and partly on the centrifugal tendency due to the earth's rotation, and that these should cause a flattening of the poles. He invented a mathematical method which he used for computing the ratio of the polar to the equatorial diameter.

He then noticed that the consequent bulging of matter at the equator would be attracted by the moon unequally, the nearest parts being most attracted; and so the moon would tend to tilt the earth when in some parts of her orbit; and the sun would do this to a less extent, because of its great distance. Then he proved that the effect ought to be a rotation of the earth's axis over a conical surface in space, exactly as the axis of a top describes a cone, if the top has a sharp point, and is set spinning and displaced from the vertical. He

actually calculated the amount; and so he explained the cause of the precession of the equinoxes discovered by Hipparchus about 150 B.C.

One of his grandest discoveries was a method of weighing the heavenly bodies by their action on each other. By means of this principle he was able to compare the mass of the sun with the masses of those planets that have moons, and also to compare the mass of our moon with the mass of the earth.

Thus Newton, after having established his great principle, devoted his splendid intellect to the calculation of its consequences. He proved that if a body be projected with any velocity in free space, subject only to a central force, varying inversely as the square of the distance, the body must revolve in a curve which may be any one of the sections of a cone–a circle, ellipse, parabola, or hyperbola; and he found that those comets of which he had observations move in parabolae round the Sun, and are thus subject to the universal law.

Newton realised that, while planets and satellites are chiefly controlled by the central body about which they revolve, the new law must involve irregularities, due to their mutual action–such, in fact, as Horrocks had indicated. He determined to put this to a test in the case of the moon, and to calculate the sun's effect, from its mass compared with that of the earth, and from its distance. He proved that the average effect upon the plane of the orbit would be to cause the line in which it cuts the plane of the ecliptic (i.e., the line of nodes) to revolve in the ecliptic once in about nineteen years. This had been a known fact from the earliest ages. He also concluded that the line of apses would revolve in the plane of the lunar orbit also in about nineteen years; but the observed period is only ten years. For a long time this was the one weak point in the Newtonian theory. It was not till 1747 that Clairaut reconciled this with the theory, and showed why Newton's calculation was not exact.

Newton proceeded to explain the other inequalities recognised by Tycho Brahe and older observers, and to calculate their maximum amounts as indicated by his theory. He further discovered from his calculations two new inequalities, one of the apogee, the other of the nodes, and assigned the maximum value. Grant has shown the values of some of these as given by observation in the tables of Meyer and more modern tables, and has compared them with the values assigned by Newton from his theory; and the comparison is very remarkable.

Newton. Modern Tables.
Â ' " Â ' "
Mean monthly motion of Apses 1.31.28 3.4.0
Mean annual motion of nodes 19.18.1,23 19.21.22,50
Mean value of "variation" 36.10 35.47
Annual equation 11.51 11.14
Inequality of mean motion of apogee 19.43 22.17

Inequality of mean motion of nodes 9.24 9.0

The only serious discrepancy is the first, which has been already mentioned. Considering that some of these perturbations had never been discovered, that the cause of none of them had ever been known, and that he exhibited his results, if he did not also make the discoveries, by the synthetic methods of geometry, it is simply marvellous that he reached to such a degree of accuracy. He invented the infinitesimal calculus which is more suited for such calculations, but had he expressed his results in that language he would have been unintelligible to many.

Newton's method of calculating the precession of the equinoxes, already referred to, is as beautiful as anything in the _Principia_. He had already proved the regression of the nodes of a satellite moving in an orbit inclined to the ecliptic. He now said that the nodes of a ring of satellites revolving round the earth's equator would consequently all regress. And if joined into a solid ring its node would regress; and it would do so, only more slowly, if encumbered by the spherical part of the earth's mass. Therefore the axis of the equatorial belt of the earth must revolve round the pole of the ecliptic. Then he set to work and found the amount due to the moon and that due to the sun, and so he solved the mystery of 2,000 years.

When Newton applied his law of gravitation to an explanation of the tides he started a new field for the application of mathematics to physical problems; and there can be little doubt that, if he could have been furnished with complete tidal observations from different parts of the world, his extraordinary powers of analysis would have enabled him to reach a satisfactory theory. He certainly opened up many mines full of intellectual gems; and his successors have never ceased in their explorations. This has led to improved mathematical methods, which, combined with the greater accuracy of observation, have rendered physical astronomy of to-day the most exact of the sciences.

Laplace only expressed the universal opinion of posterity when he said that to the _Principia_ is assured "a pre-eminence above all the other productions of the human intellect."

The name of Flamsteed, First Astronomer Royal, must here be mentioned as having supplied Newton with the accurate data required for completing the theory.

The name of Edmund Halley, Second Astronomer Royal, must ever be held in repute, not only for his own discoveries, but for the part he played in urging Newton to commit to writing, and present to the Royal Society, the results of his investigations. But for his friendly insistence it is possible that the _Principia_ would never have

been written; and but for his generosity in supplying the means the Royal Society could not have published the book.

[Illustration: DEATH MASK OF SIR ISAAC NEWTON. Photographed specially for this work from the original, by kind permission of the Royal Society, London.]

Sir Isaac Newton died in 1727, at the age of eighty-five. His body lay in state in the Jerusalem Chamber, and was buried in Westminster Abbey.

FOOTNOTES:

[1] The writer inherited from his father (Professor J. D. Forbes) a small box containing a bit of wood and a slip of paper, which had been presented to him by Sir David Brewster. On the paper Sir David had written these words: "If there be any truth in the story that Newton was led to the theory of gravitation by the fall of an apple, this bit of wood is probably a piece of the apple tree from which Newton saw the apple fall. When I was on a pilgrimage to the house in which Newton was born, I cut it off an ancient apple tree growing in his garden." When lecturing in Glasgow, about 1875, the writer showed it to his audience. The next morning, when removing his property from the lecture table, he found that his precious relic had been stolen. It would be interesting to know who has got it now!

[2] It must be noted that these words, in which the laws of gravitation are always summarised in histories and text-books, do not appear in the _Principia_; but, though they must have been composed by some early commentator, it does not appear that their origin has been traced. Nor does it appear that Newton ever extended the law beyond the Solar System, and probably his caution would have led him to avoid any statement of the kind until it should be proved.

With this exception the above statement of the law of universal gravitation contains nothing that is not to be found in the _Principia_; and the nearest approach to that statement occurs in the Seventh Proposition of Book III.:–

Prop.: That gravitation occurs in all bodies, and that it is proportional to the quantity of matter in each.

Cor. I.: The total attraction of gravitation on a planet arises, and is composed, out of the attraction on the separate parts.

Cor. II.: The attraction on separate equal particles of a body is reciprocally as the square of the distance from the particles.

[3] It is said that, when working out this final result, the probability of its confirming that part of his theory which he had

reluctantly abandoned years before excited him so keenly that he was forced to hand over his calculations to a friend, to be completed by him.

8. NEWTON'S SUCCESSORS–HALLEY, EULER, LAGRANGE, LAPLACE, ETC.

Edmund Halley succeeded Flamsteed as Second Astronomer Royal in 1721. Although he did not contribute directly to the mathematical proofs of Newton's theory, yet his name is closely associated with some of its greatest successes.

He was the first to detect the acceleration of the moon's mean motion. Hipparchus, having compared his own observations with those of more ancient astronomers, supplied an accurate value of the moon's mean motion in his time. Halley similarly deduced a value for modern times, and found it sensibly greater. He announced this in 1693, but it was not until 1749 that Dunthorne used modern lunar tables to compute a lunar eclipse observed in Babylon 721 B.C., another at Alexandria 201 B.C., a solar eclipse observed by Theon 360 A.D., and two later ones up to the tenth century. He found that to explain these eclipses Halley's suggestion must be adopted, the acceleration being 10" in one century. In 1757 Lalande again fixed it at 10."

The Paris Academy, in 1770, offered their prize for an investigation to see if this could be explained by the theory of gravitation. Euler won the prize, but failed to explain the effect, and said: "It appears to be established by indisputable evidence that the secular inequality of the moon's mean motion cannot be produced by the forces of gravitation."

The same subject was again proposed for a prize which was shared by Lagrange [1] and Euler, neither finding a solution, while the latter asserted the existence of a resisting medium in space.

Again, in 1774, the Academy submitted the same subject, a third time, for the prize; and again Lagrange failed to detect a cause in gravitation.

Laplace [2] now took the matter in hand. He tried the effect of a non-instantaneous action of gravity, to no purpose. But in 1787 he gave the true explanation. The principal effect of the sun on the moon's orbit is to diminish the earth's influence, thus lengthening the period to a new value generally taken as constant. But Laplace's calculations showed the new value to depend upon the excentricity of the earth's orbit, which, according; to theory, has a periodical variation of enormous period, and has been continually diminishing for thousands of years. Thus the solar influence has been diminishing, and the moon's mean motion increased. Laplace computed the amount at 10" in one century, agreeing with observation. (Later on Adams showed that

Laplace's calculation was wrong, and that the value he found was too large; so, part of the acceleration is now attributed by some astronomers to a lengthening of the day by tidal friction.)

Another contribution by Halley to the verification of Newton's law was made when he went to St. Helena to catalogue the southern stars. He measured the change in length of the second's pendulum in different latitudes due to the changes in gravity foretold by Newton.

Furthermore, he discovered the long inequality of Jupiter and Saturn, whose period is 929 years. For an investigation of this also the Academy of Sciences offered their prize. This led Euler to write a valuable essay disclosing a new method of computing perturbations, called the instantaneous ellipse with variable elements. The method was much developed by Lagrange.

But again it was Laplace who solved the problem of the inequalities of Jupiter and Saturn by the theory of gravitation, reducing the errors of the tables from 20' down to 12", thus abolishing the use of empirical corrections to the planetary tables, and providing another glorious triumph for the law of gravitation. As Laplace justly said: "These inequalities appeared formerly to be inexplicable by the law of gravitation–they now form one of its most striking proofs."

Let us take one more discovery of Halley, furnishing directly a new triumph for the theory. He noticed that Newton ascribed parabolic orbits to the comets which he studied, so that they come from infinity, sweep round the sun, and go off to infinity for ever, after having been visible a few weeks or months. He collected all the reliable observations of comets he could find, to the number of twenty-four, and computed their parabolic orbits by the rules laid down by Newton. His object was to find out if any of them really travelled in elongated ellipses, practically undistinguishable, in the visible part of their paths, from parabolÃ, in which case they would be seen more than once. He found two old comets whose orbits, in shape and position, resembled the orbit of a comet observed by himself in 1682. Apian observed one in 1531; Kepler the other in 1607. The intervals between these appearances is seventy-five or seventy-six years. He then examined and found old records of similar appearance in 1456, 1380, and 1305. It is true, he noticed, that the intervals varied by a year and a-half, and the inclination of the orbit to the ecliptic diminished with successive apparitions. But he knew from previous calculations that this might easily be due to planetary perturbations. Finally, he arrived at the conclusion that all of these comets were identical, travelling in an ellipse so elongated that the part where the comet was seen seemed to be part of a parabolic orbit. He then predicted its return at the end of 1758 or beginning of 1759, when he should be dead; but, as he said, "if it should return, according to our prediction, about the year 1758, impartial posterity will not refuse to acknowledge that this was first discovered by an

Englishman."[3] [_Synopsis Astronomiae Cometicae_, 1749.]

Once again Halley's suggestion became an inspiration for the mathematical astronomer. Clairaut, assisted by Lalande, found that Saturn would retard the comet 100 days, Jupiter 518 days, and predicted its return to perihelion on April 13th, 1759. In his communication to the French Academy, he said that a comet travelling into such distant regions might be exposed to the influence of forces totally unknown, and "even of some planet too far removed from the sun to be ever perceived."

The excitement of astronomers towards the end of 1758 became intense; and the honour of first catching sight of the traveller fell to an amateur in Saxony, George Palitsch, on Christmas Day, 1758. It reached perihelion on March 13th, 1759.

This fact was a startling confirmation of the Newtonian theory, because it was a new kind of calculation of perturbations, and also it added a new member to the solar system, and gave a prospect of adding many more.

When Halley's comet reappeared in 1835, Pontecoulant's computations for the date of perihelion passage were very exact, and afterwards he showed that, with more exact values of the masses of Jupiter and Saturn, his prediction was correct within two days, after an invisible voyage of seventy-five years!

Hind afterwards searched out many old appearances of this comet, going back to 11 B.C., and most of these have been identified as being really Halley's comet by the calculations of Cowell and Cromellin[4] (of Greenwich Observatory), who have also predicted its next perihelion passage for April 8th to 16th, 1910, and have traced back its history still farther, to 240 B.C.

Already, in November, 1907, the Astronomer Royal was trying to catch it by the aid of photography.

FOOTNOTES:

[1] Born 1736; died 1813.

[2] Born 1749; died 1827.

[3] This sentence does not appear in the original memoir communicated to the Royal Society, but was first published in a posthumous reprint.

[4] _R. A. S. Monthly Notices_, 1907-8.

9. DISCOVERY OF NEW PLANETS–HERSCHEL, PIAZZI, ADAMS, AND LE VERRIER.

It would be very interesting, but quite impossible in these pages, to discuss all the exquisite researches of the mathematical astronomers, and to inspire a reverence for the names connected with these researches, which for two hundred years have been establishing the universality of Newton's law. The lunar and planetary theories, the beautiful theory of Jupiter's satellites, the figure of the earth, and the tides, were mathematically treated by Maclaurin, D'Alembert, Legendre, Clairaut, Euler, Lagrange, Laplace, Walmsley, Bailly, Lalande, Delambre, Mayer, Hansen, Burchardt, Binet, Damoiseau, Plana, Poisson, Gauss, Bessel, Bouvard, Airy, Ivory, Delaunay, Le Verrier, Adams, and others of later date.

By passing over these important developments it is possible to trace some of the steps in the crowning triumph of the Newtonian theory, by which the planet Neptune was added to the known members of the solar system by the independent researches of Professor J.C. Adams and of M. Le Verrier, in 1846.

It will be best to introduce this subject by relating how the eighteenth century increased the number of known planets, which was then only six, including the earth.

On March 13th, 1781, Sir William Herschel was, as usual, engaged on examining some small stars, and, noticing that one of them appeared to be larger than the fixed stars, suspected that it might be a comet. To test this he increased his magnifying power from 227 to 460 and 932, finding that, unlike the fixed stars near it, its definition was impaired and its size increased. This convinced him that the object was a comet, and he was not surprised to find on succeeding nights that the position was changed, the motion being in the ecliptic. He gave the observations of five weeks to the Royal Society without a suspicion that the object was a new planet.

For a long time people could not compute a satisfactory orbit for the supposed comet, because it seemed to be near the perihelion, and no comet had ever been observed with a perihelion distance from the sun greater than four times the earth's distance. Lexell was the first to suspect that this was a new planet eighteen times as far from the sun as the earth is. In January, 1783, Laplace published the elliptic elements. The discoverer of a planet has a right to name it, so Herschel called it Georgium Sidus, after the king. But Lalande urged the adoption of the name Herschel. Bode suggested Uranus, and this was adopted. The new planet was found to rank in size next to Jupiter and Saturn, being 4.3 times the diameter of the earth.

In 1787 Herschel discovered two satellites, both revolving in nearly the same plane, inclined 80Â to the ecliptic, and the motion of both was retrograde.

In 1772, before Herschel's discovery, Bode[1] had discovered a curious arbitrary law of planetary distances. Opposite each planet's name write the figure 4; and, in succession, add the numbers 0, 3, 6, 12, 24, 48, 96, etc., to the 4, always doubling the last numbers. You then get the planetary distances.

Mercury, dist.– 4 4 + 0 = 4
Venus " 7 4 + 3 = 7
Earth " 10 4 + 6 = 10
Mars " 15 4 + 12 = 16
– 4 + 24 = 28
Jupiter dist. 52 4 + 48 = 52
Saturn " 95 4 + 96 = 100
(Uranus) " 192 4 + 192 = 196
– 4 + 384 = 388

All the five planets, and the earth, fitted this rule, except that there was a blank between Mars and Jupiter. When Uranus was discovered, also fitting the rule, the conclusion was irresistible that there is probably a planet between Mars and Jupiter. An association of twenty-four astronomers was now formed in Germany to search for the planet. Almost immediately afterwards the planet was discovered, not by any member of the association, but by Piazzi, when engaged upon his great catalogue of stars. On January 1st, 1801, he observed a star which had changed its place the next night. Its motion was retrograde till January 11th, direct after the 13th. Piazzi fell ill before he had enough observations for computing the orbit with certainty, and the planet disappeared in the sun's rays. Gauss published an approximate ephemeris of probable positions when the planet should emerge from the sun's light. There was an exciting hunt, and on December 31st (the day before its birthday) De Zach captured the truant, and Piazzi christened it Ceres.

The mean distance from the sun was found to be 2.767, agreeing with the 2.8 given by Bode's law. Its orbit was found to be inclined over 10Â to the ecliptic, and its diameter was only 161 miles.

On March 28th, 1802, Olbers discovered a new seventh magnitude star, which turned out to be a planet resembling Ceres. It was called Pallas. Gauss found its orbit to be inclined 35Â to the ecliptic, and to cut the orbit of Ceres; whence Olbers considered that these might be fragments of a broken-up planet. He then commenced a search for other fragments. In 1804 Harding discovered Juno, and in 1807 Olbers found Vesta. The next one was not discovered until 1845, from which date asteroids, or minor planets (as these small planets are called), have been found almost every year. They now number about 700.

It is impossible to give any idea of the interest with which the first additions since prehistoric times to the planetary system were received. All of those who showered congratulations upon the

discoverers regarded these discoveries in the light of rewards for patient and continuous labours, the very highest rewards that could be desired. And yet there remained still the most brilliant triumph of all, the addition of another planet like Uranus, before it had ever been seen, when the analysis of Adams and Le Verrier gave a final proof of the powers of Newton's great law to explain any planetary irregularity.

After Sir William Herschel discovered Uranus, in 1781, it was found that astronomers had observed it on many previous occasions, mistaking it for a fixed star of the sixth or seventh magnitude. Altogether, nineteen observations of Uranus's position, from the time of Flamsteed, in 1690, had been recorded.

In 1790 Delambre, using all these observations, prepared tables for computing its position. These worked well enough for a time, but at last the differences between the calculated and observed longitudes of the planet became serious. In 1821 Bouvard undertook a revision of the tables, but found it impossible to reconcile all the observations of 130 years (the period of revolution of Uranus is eighty-four years). So he deliberately rejected the old ones, expressing the opinion that the discrepancies might depend upon "some foreign and unperceived cause which may have been acting upon the planet." In a few years the errors even of these tables became intolerable. In 1835 the error of longitude was 30"; in 1838, 50"; in 1841, 70"; and, by comparing the errors derived from observations made before and after opposition, a serious error of the distance (radius vector) became apparent.

In 1843 John Couch Adams came out Senior Wrangler at Cambridge, and was free to undertake the research which as an undergraduate he had set himself–to see whether the disturbances of Uranus could be explained by assuming a certain orbit, and position in that orbit, of a hypothetical planet even more distant than Uranus. Such an explanation had been suggested, but until 1843 no one had the boldness to attack the problem. Bessel had intended to try, but a fatal illness overtook him.

Adams first recalculated all known causes of disturbance, using the latest determinations of the planetary masses. Still the errors were nearly as great as ever. He could now, however, use these errors as being actually due to the perturbations produced by the unknown planet.

In 1844, assuming a circular orbit, and a mean distance agreeing with Bode's law, he obtained a first approximation to the position of the supposed planet. He then asked Professor Challis, of Cambridge, to procure the latest observations of Uranus from Greenwich, which Airy immediately supplied. Then the whole work was recalculated from the beginning, with more exactness, and assuming a smaller mean distance.

In September, 1845, he handed to Challis the elements of the hypothetical planet, its mass, and its apparent position for September 30th, 1845. On September 22nd Challis wrote to Airy explaining the matter, and declaring his belief in Adams's capabilities. When Adams called on him Airy was away from home, but at the end of October, 1845, he called again, and left a paper with full particulars of his results, which had, for the most part, reduced the discrepancies to about 1". As a matter of fact, it has since been found that the heliocentric place of the new planet then given was correct within about 2Â.

Airy wrote expressing his interest, and asked for particulars about the radius vector. Adams did not then reply, as the answer to this question could be seen to be satisfactory by looking at the data already supplied. He was a most unassuming man, and would not push himself forward. He may have felt, after all the work he had done, that Airy's very natural inquiry showed no proportionate desire to search for the planet. Anyway, the matter lay in embryo for nine months.

Meanwhile, one of the ablest French astronomers, Le Verrier, experienced in computing perturbations, was independently at work, knowing nothing about Adams. He applied to his calculations every possible refinement, and, considering the novelty of the problem, his calculation was one of the most brilliant in the records of astronomy. In criticism it has been said that these were exhibitions of skill rather than helps to a solution of the particular problem, and that, in claiming to find the elements of the orbit within certain limits, he was claiming what was, under the circumstances, impossible, as the result proved.

In June, 1846, Le Verrier announced, in the _Comptes Rendus de l'Academie des Sciences_, that the longitude of the disturbing planet, for January 1st, 1847, was 325, and that the probable error did not exceed 10Â.

This result agreed so well with Adams's (within 1Â) that Airy urged Challis to apply the splendid Northumberland equatoreal, at Cambridge, to the search. Challis, however, had already prepared an exhaustive plan of attack which must in time settle the point. His first work was to observe, and make a catalogue, or chart, of all stars near Adams's position.

On August 31st, 1846, Le Verrier published the concluding part of his labours.

On September 18th, 1846, Le Verrier communicated his results to the Astronomers at Berlin, and asked them to assist in searching for the planet. By good luck Dr. Bremiker had just completed a star-chart of the very part of the heavens including Le Verrier's position; thus

eliminating all of Challis's preliminary work. The letter was received in Berlin on September 23rd; and the same evening Galle found the new planet, of the eighth magnitude, the size of its disc agreeing with Le Verrier's prediction, and the heliocentric longitude agreeing within 57'. By this time Challis had recorded, without reduction, the observations of 3,150 stars, as a commencement for his search. On reducing these, he found a star, observed on August 12th, which was not in the same place on July 30th. This was the planet, and he had also observed it on August 4th.

The feeling of wonder, admiration, and enthusiasm aroused by this intellectual triumph was overwhelming. In the world of astronomy reminders are met every day of the terrible limitations of human reasoning powers; and every success that enables the mind's eye to see a little more clearly the meaning of things has always been heartily welcomed by those who have themselves been engaged in like researches. But, since the publication of the _Principia_, in 1687, there is probably no analytical success which has raised among astronomers such a feeling of admiration and gratitude as when Adams and Le Verrier showed the inequalities in Uranus's motion to mean that an unknown planet was in a certain place in the heavens, where it was found.

At the time there was an unpleasant display of international jealousy. The British people thought that the earlier date of Adams's work, and of the observation by Challis, entitled him to at least an equal share of credit with Le Verrier. The French, on the other hand, who, on the announcement of the discovery by Galle, glowed with pride in the new proof of the great powers of their astronomer, Le Verrier, whose life had a long record of successes in calculation, were incredulous on being told that it had all been already done by a young man whom they had never heard of.

These displays of jealousy have long since passed away, and there is now universally an _entente cordiale_ that to each of these great men belongs equally the merit of having so thoroughly calculated this inverse problem of perturbations as to lead to the immediate discovery of the unknown planet, since called Neptune.

It was soon found that the planet had been observed, and its position recorded as a fixed star by Lalande, on May 8th and 10th, 1795.

Mr. Lassel, in the same year, 1846, with his two-feet reflector, discovered a satellite, with retrograde motion, which gave the mass of the planet about a twentieth of that of Jupiter.

FOOTNOTES:

[1] Bode's law, or something like it, had already been fore-shadowed by Kepler and others, especially Titius (see _Monatliche

Correspondenz_, vol. vii., p. 72).

BOOK III. OBSERVATION

10. INSTRUMENTS OF PRECISION–STATE OF THE SOLAR SYSTEM.

Having now traced the progress of physical astronomy up to the time when very striking proofs of the universality of the law of gravitation convinced the most sceptical, it must still be borne in mind that, while gravitation is certainly the principal force governing the motions of the heavenly bodies, there may yet be a resisting medium in space, and there may be electric and magnetic forces to deal with. There may, further, be cases where the effects of luminous radiative repulsion become apparent, and also Crookes' vacuum-effects described as "radiant matter." Nor is it quite certain that Laplace's proofs of the instantaneous propagation of gravity are final.

And in the future, as in the past, Tycho Brahe's dictum must be maintained, that all theory shall be preceded by accurate observations. It is the pride of astronomers that their science stands above all others in the accuracy of the facts observed, as well as in the rigid logic of the mathematics used for interpreting these facts.

It is interesting to trace historically the invention of those instruments of precision which have led to this result, and, without entering on the details required in a practical handbook, to note the guiding principles of construction in different ages.

It is very probable that the Chaldeans may have made spheres, like the armillary sphere, for representing the poles of the heavens; and with rings to show the ecliptic and zodiac, as well as the equinoctial and solstitial colures; but we have no record. We only know that the tower of Belus, on an eminence, was their observatory. We have, however, distinct records of two such spheres used by the Chinese about 2500 B.C. Gnomons, or some kind of sundial, were used by the Egyptians and others; and many of the ancient nations measured the obliquity of the ecliptic by the shadows of a vertical column in summer and winter. The natural horizon was the only instrument of precision used by those who determined star positions by the directions of their risings and settings; while in those days the clepsydra, or waterclock, was the best instrument for comparing their times of rising and setting.

About 300 B.C. an observatory fitted with circular instruments for star positions was set up at Alexandria, the then centre of civilisation. We know almost nothing about the instruments used by Hipparchus in preparing his star catalogues and his lunar and solar tables; but the invention of the astrolabe is attributed to him.[1]

In more modern times Nuremberg became a centre of astronomical

culture. Waltherus, of that town, made really accurate observations of star altitudes, and of the distances between stars; and in 1484 A.D. he used a kind of clock. Tycho Brahe tried these, but discarded them as being inaccurate.

Tycho Brahe (1546-1601 A.D.) made great improvements in armillary spheres, quadrants, sextants, and large celestial globes. With these he measured the positions of stars, or the distance of a comet from several known stars. He has left us full descriptions of them, illustrated by excellent engravings. Previous to his time such instruments were made of wood. Tycho always used metal. He paid the greatest attention to the stability of mounting, to the orientation of his instruments, to the graduation of the arcs by the then new method of transversals, and to the aperture sight used upon his pointer. There were no telescopes in his day, and no pendulum clocks. He recognised the fact that there must be instrumental errors. He made these as small as was possible, measured their amount, and corrected his observations. His table of refractions enabled him to abolish the error due to our atmosphere so far as it could affect naked-eye observations. The azimuth circle of Tycho's largest quadrant had a diameter of nine feet, and the quadrant a radius of six feet. He introduced the mural quadrant for meridian observations.[2]

[Illustration: ANCIENT CHINESE INSTRUMENTS, Including quadrant, celestial globe, and two armillae, in the Observatory at Peking. Photographed in Peking by the author in 1875, and stolen by the Germans when the Embassies were relieved by the allies in 1900.]

The French Jesuits at Peking, in the seventeenth century, helped the Chinese in their astronomy. In 1875 the writer saw and photographed, on that part of the wall of Peking used by the Mandarins as an observatory, the six instruments handsomely designed by Father Verbiest, copied from the instruments of Tycho Brahe, and embellished with Chinese dragons and emblems cast on the supports. He also saw there two old instruments (which he was told were Arabic) of date 1279, by Ko Show-King, astronomer to Koblai Khan, the grandson of Chenghis Khan. One of these last is nearly identical with the armillae of Tycho; and the other with his "armillae Ãquatorià maximÃ," with which he observed the comet of 1585, besides fixed stars and planets.[3]

The discovery by Galileo of the isochronism of the pendulum, followed by Huyghens's adaptation of that principle to clocks, has been one of the greatest aids to accurate observation. About the same time an equally beneficial step was the employment of the telescope as a pointer; not the Galilean with concave eye-piece, but with a magnifying glass to examine the focal image, at which also a fixed mark could be placed. Kepler was the first to suggest this. Gascoigne was the first to use it. Huyghens used a metal strip of variable width

in the focus, as a micrometer to cover a planetary disc, and so to measure the width covered by the planet. The Marquis Malvasia, in 1662, described the network of fine silver threads at right angles, which he used in the focus, much as we do now.

In the hands of such a skilful man as Tycho Brahe, the old open sights, even without clocks, served their purpose sufficiently well to enable Kepler to discover the true theory of the solar system. But telescopic sights and clocks were required for proving some of Newton's theories of planetary perturbations. Picard's observations at Paris from 1667 onwards seem to embody the first use of the telescope as a pointer. He was also the first to introduce the use of Huyghens's clocks for observing the right ascension of stars. Olaus Romer was born at Copenhagen in 1644. In 1675, by careful study of the times of eclipses of Jupiter's satellites, he discovered that light took time to traverse space. Its velocity is 186,000 miles per second. In 1681 he took up his duties as astronomer at Copenhagen, and built the first transit circle on a window-sill of his house. The iron axis was five feet long and one and a-half inches thick, and the telescope was fixed near one end with a counterpoise. The telescope-tube was a double cone, to prevent flexure. Three horizontal and three vertical wires were used in the focus. These were illuminated by a speculum, near the object-glass, reflecting the light from a lantern placed over the axis, the upper part of the telescope-tube being partly cut away to admit the light. A divided circle, with pointer and reading microscope, was provided for reading the declination. He realised the superiority of a circle with graduations over a much larger quadrant. The collimation error was found by reversing the instrument and using a terrestrial mark, the azimuth error by star observations. The time was expressed in fractions of a second. He also constructed a telescope with equatoreal mounting, to follow a star by one axial motion. In 1728 his instruments and observation records were destroyed by fire.

Hevelius had introduced the vernier and tangent screw in his measurement of arc graduations. His observatory and records were burnt to the ground in 1679. Though an old man, he started afresh, and left behind him a catalogue of 1,500 stars.

Flamsteed began his duties at Greenwich Observatory, as first Astronomer Royal, in 1676, with very poor instruments. In 1683 he put up a mural arc of 140Â, and in 1689 a better one, seventy-nine inches radius. He conducted his measurements with great skill, and introduced new methods to attain accuracy, using certain stars for determining the errors of his instruments; and he always reduced his observations to a form in which they could be readily used. He introduced new methods for determining the position of the equinox and the right ascension of a fundamental star. He produced a catalogue of 2,935 stars. He supplied Sir Isaac Newton with results of observation required in his theoretical calculations. He died in 1719.

Halley succeeded Flamsteed to find that the whole place had been gutted by the latter's executors. In 1721 he got a transit instrument, and in 1726 a mural quadrant by Graham. His successor in 1742, Bradley, replaced this by a fine brass quadrant, eight feet radius, by Bird; and Bradley's zenith sector was purchased for the observatory. An instrument like this, specially designed for zenith stars, is capable of greater rigidity than a more universal instrument; and there is no trouble with refraction in the zenith. For these reasons Bradley had set up this instrument at Kew, to attempt the proof of the earth's motion by observing the annual parallax of stars. He certainly found an annual variation of zenith distance, but not at the times of year required by the parallax. This led him to the discovery of the "aberration" of light and of nutation. Bradley has been described as the founder of the modern system of accurate observation. He died in 1762, leaving behind him thirteen folio volumes of valuable but unreduced observations. Those relating to the stars were reduced by Bessel and published in 1818, at KÃnigsberg, in his well-known standard work, _Fundamenta Astronomiae_. In it are results showing the laws of refraction, with tables of its amount, the maximum value of aberration, and other constants.

Bradley was succeeded by Bliss, and he by Maskelyne (1765), who carried on excellent work, and laid the foundations of the Nautical Almanac (1767). Just before his death he induced the Government to replace Bird's quadrant by a fine new mural _circle_, six feet in diameter, by Troughton, the divisions being read off by microscopes fixed on piers opposite to the divided circle. In this instrument the micrometer screw, with a divided circle for turning it, was applied for bringing the micrometer wire actually in line with a division on the circle–a plan which is still always adopted.

Pond succeeded Maskelyne in 1811, and was the first to use this instrument. From now onwards the places of stars were referred to the pole, not to the zenith; the zero being obtained from measures on circumpolar stars. Standard stars were used for giving the clock error. In 1816 a new transit instrument, by Troughton, was added, and from this date the Greenwich star places have maintained the very highest accuracy.

George Biddell Airy, Seventh Astronomer Royal,[4] commenced his Greenwich labours in 1835. His first and greatest reformation in the work of the observatory was one he had already established at Cambridge, and is now universally adopted. He held that an observation is not completed until it has been reduced to a useful form; and in the case of the sun, moon, and planets these results were, in every case, compared with the tables, and the tabular error printed.

Airy was firmly impressed with the object for which Charles II. had wisely founded the observatory in connection with navigation, and for

observations of the moon. Whenever a meridian transit of the moon could be observed this was done. But, even so, there are periods in the month when the moon is too near the sun for a transit to be well observed. Also weather interferes with many meridian observations. To render the lunar observations more continuous, Airy employed Troughton's successor, James Simms, in conjunction with the engineers, Ransome and May, to construct an altazimuth with three-foot circles, and a five-foot telescope, in 1847. The result was that the number of lunar observations was immediately increased threefold, many of them being in a part of the moon's orbit which had previously been bare of observations. From that date the Greenwich lunar observations have been a model and a standard for the whole world.

Airy also undertook to superintend the reduction of all Greenwich lunar observations from 1750 to 1830. The value of this laborious work, which was completed in 1848, cannot be over-estimated.

The demands of astronomy, especially in regard to small minor planets, required a transit instrument and mural circle with a more powerful telescope. Airy combined the functions of both, and employed the same constructors as before to make a _transit-circle_ with a telescope of eleven and a-half feet focus and a circle of six-feet diameter, the object-glass being eight inches in diameter.

Airy, like Bradley, was impressed with the advantage of employing stars in the zenith for determining the fundamental constants of astronomy. He devised a _reflex zenith tube_, in which the zenith point was determined by reflection from a surface of mercury. The design was so simple, and seemed so perfect, that great expectations were entertained. But unaccountable variations comparable with those of the transit circle appeared, and the instrument was put out of use until 1903, when the present Astronomer Royal noticed that the irregularities could be allowed for, being due to that remarkable variation in the position of the earth's axis included in circles of about six yards diameter at the north and south poles, discovered at the end of the nineteenth century. The instrument is now being used for investigating these variations; and in the year 1907 as many as 1,545 observations of stars were made with the reflex zenith tube.

In connection with zenith telescopes it must be stated that Respighi, at the Capitol Observatory at Rome, made use of a deep well with a level mercury surface at the bottom and a telescope at the top pointing downwards, which the writer saw in 1871. The reflection of the micrometer wires and of a star very near the zenith (but not quite in the zenith) can be observed together. His mercury trough was a circular plane surface with a shallow edge to retain the mercury. The surface quickly came to rest after disturbance by street traffic.

Sir W. M. H. Christie, Eighth Astronomer Royal, took up his duties in that capacity in 1881. Besides a larger altazimuth that he erected in

1898, he has widened the field of operations at Greenwich by the extensive use of photography and the establishment of large equatoreals. From the point of view of instruments of precision, one of the most important new features is the astrographic equatoreal, set up in 1892 and used for the Greenwich section of the great astrographic chart just completed. Photography has come to be of use, not only for depicting the sun and moon, comets and nebulae, but also to obtain accurate relative positions of neighbouring stars; to pick up objects that are invisible in any telescope; and, most of all perhaps, in fixing the positions of faint satellites. Thus Saturn's distant satellite, Phoebe, and the sixth and seventh satellites of Jupiter, have been followed regularly in their courses at Greenwich ever since their discovery with the thirty-inch reflector (erected in 1897); and while doing so Mr. Melotte made, in 1908, the splendid discovery on some of the photographic plates of an eighth satellite of Jupiter, at an enormous distance from the planet. From observations in the early part of 1908, over a limited arc of its orbit, before Jupiter approached the sun, Mr. Cowell computed a retrograde orbit and calculated the future positions of this satellite, which enabled Mr. Melotte to find it again in the autumn–a great triumph both of calculation and of photographic observation. This satellite has never been seen, and has been photographed only at Greenwich, Heidelberg, and the Lick Observatory.

Greenwich Observatory has been here selected for tracing the progress of accurate measurement. But there is one instrument of great value, the heliometer, which is not used at Greenwich. This serves the purpose of a double image micrometer, and is made by dividing the object-glass of a telescope along a diameter. Each half is mounted so as to slide a distance of several inches each way on an arc whose centre is the focus. The amount of the movement can be accurately read. Thus two fields of view overlap, and the adjustment is made to bring an image of one star over that of another star, and then to do the same by a displacement in the opposite direction. The total movement of the half-object glass is double the distance between the star images in the focal plane. Such an instrument has long been established at Oxford, and German astronomers have made great use of it. But in the hands of Sir David Gill (late His Majesty's Astronomer at the Cape of Good Hope), and especially in his great researches on Solar and on Stellar parallax, it has been recognised as an instrument of the very highest accuracy, measuring the distance between stars correctly to less than a tenth of a second of arc.

The superiority of the heliometer over all other devices (except photography) for measuring small angles has been specially brought into prominence by Sir David Gill's researches on the distance of the sun–_i.e.,_ the scale of the solar system. A measurement of the distance of any planet fixes the scale, and, as Venus approaches the earth most nearly of all the planets, it used to be supposed that a Transit of Venus offered the best opportunity for such measurement,

especially as it was thought that, as Venus entered on the solar disc, the sweep of light round the dark disc of Venus would enable a very precise observation to be made. The Transit of Venus in 1874, in which the present writer assisted, overthrew this delusion.

In 1877 Sir David Gill used Lord Crawford's heliometer at the Island of Ascension to measure the parallax of Mars in opposition, and found the sun's distance 93,080,000 miles. He considered that, while the superiority of the heliometer had been proved, the results would be still better with the points of light shown by minor planets rather than with the disc of Mars.

In 1888-9, at the Cape, he observed the minor planets Iris, Victoria, and Sappho, and secured the co-operation of four other heliometers. His final result was 92,870,000 miles, the parallax being 8",802 (_Cape Obs_., Vol. VI.).

So delicate were these measures that Gill detected a minute periodic error of theory of twenty-seven days, owing to a periodically erroneous position of the centre of gravity of the earth and moon to which the position of the observer was referred. This led him to correct the mass of the moon, and to fix its ratio to the earth's mass = 0.012240.

Another method of getting the distance from the sun is to measure the velocity of the earth's orbital motion, giving the circumference traversed in a year, and so the radius of the orbit. This has been done by comparing observation and experiment. The aberration of light is an angle 20" 48, giving the ratio of the earth's velocity to the velocity of light. The velocity of light is 186,000 miles a second; whence the distance to the sun is 92,780,000 miles. There seems, however, to be some uncertainty about the true value of the aberration, any determination of which is subject to irregularities due to the "seasonal errors." The velocity of light was experimentally found, in 1862, by Fizeau and Foucault, each using an independent method. These methods have been developed, and new values found, by Cornu, Michaelson, Newcomb, and the present writer.

Quite lately Halm, at the Cape of Good Hope, measured spectroscopically the velocity of the earth to and from a star by observations taken six months apart. Thence he obtained an accurate value of the sun's distance.[5]

But the remarkably erratic minor planet, Eros, discovered by Witte in 1898, approaches the earth within 15,000,000 miles at rare intervals, and, with the aid of photography, will certainly give us the best result. A large number of observatories combined to observe the opposition of 1900. Their results are not yet completely reduced, but the best value deduced so far for the parallax[6] is 8".807 Âł 0".0028.[7]

FOOTNOTES:

[1] In 1480 Martin Behaim, of Nuremberg, produced his _astrolabe_ for measuring the latitude, by observation of the sun, at sea. It consisted of a graduated metal circle, suspended by a ring which was passed over the thumb, and hung vertically. A pointer was fixed to a pin at the centre. This arm, called the _alhidada_, worked round the graduated circle, and was pointed to the sun. The altitude of the sun was thus determined, and, by help of solar tables, the latitude could be found from observations made at apparent noon.

[2] See illustration on p. 76.

[3] See Dreyer's article on these instruments in _Copernicus_, Vol. I. They were stolen by the Germans after the relief of the Embassies, in 1900. The best description of these instruments is probably that contained in an interesting volume, which may be seen in the library of the R. A. S., entitled _Chinese Researches_, by Alexander Wyllie (Shanghai, 1897).

[4] Sir George Airy was very jealous of this honourable title. He rightly held that there is only one Astronomer Royal at a time, as there is only one Mikado, one Dalai Lama. He said that His Majesty's Astronomer at the Cape of Good Hope, His Majesty's Astronomer for Scotland, and His Majesty's Astronomer for Ireland are not called Astronomers Royal.

[5] _Annals of the Cape Observatory_, vol. x., part 3.

[6] The parallax of the sun is the angle subtended by the earth's radius at the sun's distance.

[7] A. R. Hinks, R.A.S.; _Monthly Notices_, June, 1909.

11. HISTORY OF THE TELESCOPE

Accounts of wonderful optical experiments by Roger Bacon (who died in 1292), and in the sixteenth century by Digges, Baptista Porta, and Antonio de Dominis (Grant, _Hist. Ph. Ast_.), have led some to suppose that they invented the telescope. The writer considers that it is more likely that these notes refer to a kind of _camera obscura_, in which a lens throws an inverted image of a landscape on the wall.

The first telescopes were made in Holland, the originator being either Henry Lipperhey,[1] Zacharias Jansen, or James Metius, and the date 1608 or earlier.

In 1609 Galileo, being in Venice, heard of the invention, went home and worked out the theory, and made a similar telescope. These telescopes were all made with a convex object-glass and a concave eye-lens, and this type is spoken of as the Galilean telescope. Its defects are that it has no real focus where cross-wires can be placed, and that the field of view is very small. Kepler suggested the convex eye-lens in 1611, and Scheiner claimed to have used one in 1617. But it was Huyghens who really introduced them. In the seventeenth century telescopes were made of great length, going up to 300 feet. Huyghens also invented the compound eye-piece that bears his name, made of two convex lenses to diminish spherical aberration.

But the defects of colour remained, although their cause was unknown until Newton carried out his experiments on dispersion and the solar spectrum. To overcome the spherical aberration James Gregory,[2] of Aberdeen and Edinburgh, in 1663, in his _Optica Promota_, proposed a reflecting speculum of parabolic form. But it was Newton, about 1666, who first made a reflecting telescope; and he did it with the object of avoiding colour dispersion.

Some time elapsed before reflectors were much used. Pound and Bradley used one presented to the Royal Society by Hadley in 1723. Hawksbee, Bradley, and Molyneaux made some. But James Short, of Edinburgh, made many excellent Gregorian reflectors from 1732 till his death in 1768.

Newton's trouble with refractors, chromatic aberration, remained insurmountable until John Dollond (born 1706, died 1761), after many experiments, found out how to make an achromatic lens out of two lenses–one of crown glass, the other of flint glass–to destroy the colour, in a way originally suggested by Euler. He soon acquired a great reputation for his telescopes of moderate size; but there was a difficulty in making flint-glass lenses of large size. The first actual inventor and constructor of an achromatic telescope was Chester Moor Hall, who was not in trade, and did not patent it. Towards the close of the eighteenth century a Swiss named Guinand at last succeeded in producing larger flint-glass discs free from striae. Frauenhofer, of Munich, took him up in 1805, and soon produced, among others, Struve's Dorpat refractor of 9.9 inches diameter and 13.5 feet focal length, and another, of 12 inches diameter and 18 feet focal length, for Lamont, of Munich.

In the nineteenth century gigantic _reflectors_ have been made. Lassel's 2-foot reflector, made by himself, did much good work, and discovered four new satellites. But Lord Rosse's 6-foot reflector, 54 feet focal length, constructed in 1845, is still the largest ever made. The imperfections of our atmosphere are against the use of such large apertures, unless it be on high mountains. During the last half century excellent specula have been made of silvered glass, and Dr. Common's 5-foot speculum (removed, since his death, to Harvard) has done excellent work. Then there are the 5-foot

Yerkes reflector at Chicago, and the 4-foot by Grubb at Melbourne.

Passing now from these large reflectors to refractors, further improvements have been made in the manufacture of glass by Chance, of Birmingham, Feil and Mantois, of Paris, and Schott, of Jena; while specialists in grinding lenses, like Alvan Clark, of the U.S.A., and others, have produced many large refractors.

Cooke, of York, made an object-glass, 25-inch diameter, for Newall, of Gateshead, which has done splendid work at Cambridge. We have the Washington 26-inch by Clark, the Vienna 27-inch by Grubb, the Nice 29Â-inch by Gautier, the Pulkowa 30-inch by Clark. Then there was the sensation of Clark's 36-inch for the Lick Observatory in California, and finally his _tour de force_, the Yerkes 40-inch refractor, for Chicago.

At Greenwich there is the 28-inch photographic refractor, and the Thompson equatoreal by Grubb, carrying both the 26-inch photographic refractor and the 30-inch reflector. At the Cape of Good Hope we find Mr. Frank McClean's 24-inch refractor, with an object-glass prism for spectroscopic work.

It would be out of place to describe here the practical adjuncts of a modern equatoreal–the adjustments for pointing it, the clock for driving it, the position-micrometer and various eye-pieces, the photographic and spectroscopic attachments, the revolving domes, observing seats, and rising floors and different forms of mounting, the siderostats and coelostats, and other convenient adjuncts, besides the registering chronograph and numerous facilities for aiding observation. On each of these a chapter might be written; but the most important part of the whole outfit is the man behind the telescope, and it is with him that a history is more especially concerned.

SPECTROSCOPE.

Since the invention of the telescope no discovery has given so great an impetus to astronomical physics as the spectroscope; and in giving us information about the systems of stars and their proper motions it rivals the telescope.

Frauenhofer, at the beginning of the nineteenth century, while applying Dollond's discovery to make large achromatic telescopes, studied the dispersion of light by a prism. Admitting the light of the sun through a narrow slit in a window-shutter, an inverted image of the slit can be thrown, by a lens of suitable focal length, on the wall opposite. If a wedge or prism of glass be interposed, the image is deflected to one side; but, as Newton had shown, the images formed by the different colours of which white light is composed are deflected to different extents–the violet most, the red least. The

number of colours forming images is so numerous as to form a continuous spectrum on the wall with all the colours–red, orange, yellow, green, blue, indigo, and violet. But Frauenhofer found with a narrow slit, well focussed by the lens, that some colours were missing in the white light of the sun, and these were shown by dark lines across the spectrum. These are the Frauenhofer lines, some of which he named by the letters of the alphabet. The D line is a very marked one in the yellow. These dark lines in the solar spectrum had already been observed by Wollaston. [3]

On examining artificial lights it was found that incandescent solids and liquids (including the carbon glowing in a white gas flame) give continuous spectra; gases, except under enormous pressure, give bright lines. If sodium or common salt be thrown on the colourless flame of a spirit lamp, it gives it a yellow colour, and its spectrum is a bright yellow line agreeing in position with line D of the solar spectrum.

In 1832 Sir David Brewster found some of the solar black lines increased in strength towards sunset, and attributed them to absorption in the earth's atmosphere. He suggested that the others were due to absorption in the sun's atmosphere. Thereupon Professor J. D. Forbes pointed out that during a nearly total eclipse the lines ought to be strengthened in the same way; as that part of the sun's light, coming from its edge, passes through a great distance in the sun's atmosphere. He tried this with the annular eclipse of 1836, with a negative result which has never been accounted for, and which seemed to condemn Brewster's view.

In 1859 Kirchoff, on repeating Frauenhofer's experiment, found that, if a spirit lamp with salt in the flame were placed in the path of the light, the black D line is intensified. He also found that, if he used a limelight instead of the sunlight and passed it through the flame with salt, the spectrum showed the D line black; or the vapour of sodium absorbs the same light that it radiates. This proved to him the existence of sodium in the sun's atmosphere.[4] Iron, calcium, and other elements were soon detected in the same way.

Extensive laboratory researches (still incomplete) have been carried out to catalogue (according to their wave-length on the undulatory theory of light) all the lines of each chemical element, under all conditions of temperature and pressure. At the same time, all the lines have been catalogued in the light of the sun and the brighter of the stars.

Another method of obtaining spectra had long been known, by transmission through, or reflection from, a grating of equidistant lines ruled upon glass or metal. H. A. Rowland developed the art of constructing these gratings, which requires great technical skill, and for this astronomers owe him a debt of gratitude.

In 1842 Doppler[5] proved that the colour of a luminous body, like the pitch or note of a sounding body, must be changed by velocity of approach or recession. Everyone has noticed on a railway that, on meeting a locomotive whistling, the note is lowered after the engine has passed. The pitch of a sound or the colour of a light depends on the number of waves striking the ear or eye in a second. This number is increased by approach and lowered by recession.

Thus, by comparing the spectrum of a star alongside a spectrum of hydrogen, we may see all the lines, and be sure that there is hydrogen in the star; yet the lines in the star-spectrum may be all slightly displaced to one side of the lines of the comparison spectrum. If towards the violet end, it means mutual approach of the star and earth; if to the red end, it means recession. The displacement of lines does not tell us whether the motion is in the star, the earth, or both. The displacement of the lines being measured, we can calculate the rate of approach or recession in miles per second.

In 1868 Huggins[6] succeeded in thus measuring the velocities of stars in the direction of the line of sight.

In 1873 Vogel[7] compared the spectra of the sun's East (approaching) limb and West (receding) limb, and the displacement of lines endorsed the theory. This last observation was suggested by ZÃllner.

FOOTNOTES:

[1] In the _Encyclopaedia Britannica_, article "Telescope," and in Grant's _Physical Astronomy_, good reasons are given for awarding the honour to Lipperhey.

[2] Will the indulgent reader excuse an anecdote which may encourage some workers who may have found their mathematics defective through want of use? James Gregory's nephew David had a heap of MS. notes by Newton. These descended to a Miss Gregory, of Edinburgh, who handed them to the present writer, when an undergraduate at Cambridge, to examine. After perusal, he lent them to his kindest of friends, J. C. Adams (the discoverer of Neptune), for his opinion. Adams's final verdict was: "I fear they are of no value. It is pretty evident that, when he wrote these notes, _Newton's mathematics were a little rusty_."

[3] _R. S. Phil. Trans_.

[4] The experiment had been made before by one who did not understand its meaning;. But Sir George G. Stokes had already given verbally the true explanation of Frauenhofer lines.

[5] _Abh. d. KÃn. BÃhm. d. Wiss_., Bd. ii., 1841-42, p. 467. See also Fizeau in the _Ann. de Chem. et de Phys_., 1870, p. 211.

[6] _R. S. Phil. Trans_., 1868.

[7] _Ast. Nach_., No. 1, 864.

BOOK IV. THE PHYSICAL PERIOD

We have seen how the theory of the solar system was slowly developed by the constant efforts of the human mind to find out what are the rules of cause and effect by which our conception of the present universe and its development seems to be bound. In the primitive ages a mere record of events in the heavens and on the earth gave the only hope of detecting those uniform sequences from which to derive rules or laws of cause and effect upon which to rely. Then came the geometrical age, in which rules were sought by which to predict the movements of heavenly bodies. Later, when the relation of the sun to the courses of the planets was established, the sun came to be looked upon as a cause; and finally, early in the seventeenth century, for the first time in history, it began to be recognised that the laws of dynamics, exactly as they had been established for our own terrestrial world, hold good, with the same rigid invariability, at least as far as the limits of the solar system.

Throughout this evolution of thought and conjecture there were two types of astronomers–those who supplied the facts, and those who supplied the interpretation through the logic of mathematics. So Ptolemy was dependent upon Hipparchus, Kepler on Tycho Brahe, and Newton in much of his work upon Flamsteed.

When Galileo directed his telescope to the heavens, when Secchi and Huggins studied the chemistry of the stars by means of the spectroscope, and when Warren De la Rue set up a photoheliograph at Kew, we see that a progress in the same direction as before, in the evolution of our conception of the universe, was being made. Without definite expression at any particular date, it came to be an accepted fact that not only do earthly dynamics apply to the heavenly bodies, but that the laws we find established here, in geology, in chemistry, and in the laws of heat, may be extended with confidence to the heavenly bodies. Hence arose the branch of astronomy called astronomical physics, a science which claims a large portion of the work of the telescope, spectroscope, and photography. In this new development it is more than ever essential to follow the dictum of Tycho Brahe–not to make theories until all the necessary facts are obtained. The great astronomers of to-day still hold to Sir Isaac Newton's declaration, "Hypotheses non fingo." Each one may have his suspicions of a theory to guide him in a course of observation, and may call it a working hypothesis. But the cautious astronomer does not proclaim these to the world; and the historian is certainly not justified in including in his record those vague speculations founded on incomplete data which may be demolished to-morrow, and which,

however attractive they may be, often do more harm than good to the progress of true science. Meanwhile the accumulation of facts has been prodigious, and the revelations of the telescope and spectroscope entrancing.

12. THE SUN.

One of Galileo's most striking discoveries, when he pointed his telescope to the heavenly bodies, was that of the irregularly shaped spots on the sun, with the dark central _umbra_ and the less dark, but more extensive, _penumbra_ surrounding it, sometimes with several umbrae in one penumbra. He has left us many drawings of these spots, and he fixed their period of rotation as a lunar month.

[Illustration: SOLAR SURFACE, As Photographed at the Royal Observatory, Greenwich, showing sun-spots with umbrae, penumbrae, and faculae.]

It is not certain whether Galileo, Fabricius, or Schemer was the first to see the spots. They all did good work. The spots were found to be ever varying in size and shape. Sometimes, when a spot disappears at the western limb of the sun, it is never seen again. In other cases, after a fortnight, it reappears at the eastern limb. The faculae, or bright areas, which are seen all over the sun's surface, but specially in the neighbourhood of spots, and most distinctly near the sun's edge, were discovered by Galileo. A high telescopic power resolves their structure into an appearance like willow-leaves, or rice-grains, fairly uniform in size, and more marked than on other parts of the sun's surface.

Speculations as to the cause of sun-spots have never ceased from Galileo's time to ours. He supposed them to be clouds. Scheiner[1] said they were the indications of tumultuous movements occasionally agitating the ocean of liquid fire of which he supposed the sun to be composed.

A. Wilson, of Glasgow, in 1769,[2] noticed a movement of the umbra relative to the penumbra in the transit of the spot over the sun's surface; exactly as if the spot were a hollow, with a black base and grey shelving sides. This was generally accepted, but later investigations have contradicted its universality. Regarding the cause of these hollows, Wilson said:–

Whether their first production and subsequent numberless changes depend upon the eructation of elastic vapours from below, or upon eddies or whirlpools commencing at the surface, or upon the dissolving of the luminous matter in the solar atmosphere, as clouds are melted and again given out by our air; or, if the reader pleases, upon the annihilation and reproduction of parts of this resplendent covering, is left for theory to guess at.[3]

Ever since that date theory has been guessing at it. The solar astronomer is still applying all the instruments of modern research to find out which of these suppositions, or what modification of any of them, is nearest the truth. The obstacle–one that is perhaps fatal to a real theory–lies in the impossibility of reproducing comparative experiments in our laboratories or in our atmosphere.

Sir William Herschel propounded an explanation of Wilson's observation which received much notice, but which, out of respect for his memory, is not now described, as it violated the elementary laws of heat.

Sir John Herschel noticed that the spots are mostly confined to two zones extending to about 35Â on each side of the equator, and that a zone of equatoreal calms is free from spots. But it was R. C. Carrington[4] who, by his continuous observations at Redhill, in Surrey, established the remarkable fact that, while the rotation period in the highest latitudes, 50Â, where spots are seen, is twenty-seven-and-a-half days, near the equator the period is only twenty-five days. His splendid volume of observations of the sun led to much new information about the average distribution of spots at different epochs.

Schwabe, of Dessau, began in 1826 to study the solar surface, and, after many years of work, arrived at a law of frequency which has been more fruitful of results than any discovery in solar physics.[5] In 1843 he announced a decennial period of maxima and minima of sun-spot displays. In 1851 it was generally accepted, and, although a period of eleven years has been found to be more exact, all later observations, besides the earlier ones which have been hunted up for the purpose, go to establish a true periodicity in the number of sun-spots. But quite lately Schuster[6] has given reasons for admitting a number of co-existent periods, of which the eleven-year period was predominant in the nineteenth century.

In 1851 Lament, a Scotchman at Munich, found a decennial period in the daily range of magnetic declination. In 1852 Sir Edward Sabine announced a similar period in the number of "magnetic storms" affecting all of the three magnetic elements–declination, dip, and intensity. Australian and Canadian observations both showed the decennial period in all three elements. Wolf, of Zurich, and Gauthier, of Geneva, each independently arrived at the same conclusion.

It took many years before this coincidence was accepted as certainly more than an accident by the old-fashioned astronomers, who want rigid proof for every new theory. But the last doubts have long vanished, and a connection has been further traced between violent outbursts of solar activity and simultaneous magnetic storms.

The frequency of the Aurora Borealis was found by Wolf to follow the

same period. In fact, it is closely allied in its cause to terrestrial magnetism. Wolf also collected old observations tracing the periodicity of sun-spots back to about 1700 A.D.

Spoerer deduced a law of dependence of the average latitude of sun-spots on the phase of the sun-spot period.

All modern total solar eclipse observations seem to show that the shape of the luminous corona surrounding the moon at the moment of totality has a special distinct character during the time of a sun-spot maximum, and another, totally different, during a sun-spot minimum.

A suspicion is entertained that the total quantity of heat received by the earth from the sun is subject to the same period. This would have far-reaching effects on storms, harvests, vintages, floods, and droughts; but it is not safe to draw conclusions of this kind except from a very long period of observations.

Solar photography has deprived astronomers of the type of Carrington of the delight in devoting a life's work to collecting data. It has now become part of the routine work of an observatory.

In 1845 Foucault and Fizeau took a daguerreotype photograph of the sun. In 1850 Bond produced one of the moon of great beauty, Draper having made some attempts at an even earlier date. But astronomical photography really owes its beginning to De la Rue, who used the collodion process for the moon in 1853, and constructed the Kew photoheliograph in 1857, from which date these instruments have been multiplied, and have given us an accurate record of the sun's surface. Gelatine dry plates were first used by Huggins in 1876.

It is noteworthy that from the outset De la Rue recognised the value of stereoscopic vision, which is now known to be of supreme accuracy. In 1853 he combined pairs of photographs of the moon in the same phase, but under different conditions regarding libration, showing the moon from slightly different points of view. These in the stereoscope exhibited all the relief resulting from binocular vision, and looked like a solid globe. In 1860 he used successive photographs of the total solar eclipse stereoscopically, to prove that the red prominences belong to the sun, and not to the moon. In 1861 he similarly combined two photographs of a sun-spot, the perspective effect showing the umbra like a floor at the bottom of a hollow penumbra; and in one case the faculÃ were discovered to be sailing over a spot apparently at some considerable height. These appearances may be partly due to a proper motion; but, so far as it went, this was a beautiful confirmation of Wilson's discovery. Hewlett, however, in 1894, after thirty years of work, showed that the spots are not always depressions, being very subject to disturbance.

The Kew photographs [7] contributed a vast amount of information about sun-spots, and they showed that the faculÃ generally follow the spots in their rotation round the sun.

The constitution of the sun's photosphere, the layer which is the principal light-source on the sun, has always been a subject of great interest; and much was done by men with exceptionally keen eyesight, like Mr. Dawes. But it was a difficult subject, owing to the rapidity of the changes in appearance of the so-called rice-grains, about 1" in diameter. The rapid transformations and circulations of these rice-grains, if thoroughly studied, might lead to a much better knowledge of solar physics. This seemed almost hopeless, as it was found impossible to identify any "rice-grain" in the turmoil after a few minutes. But M. Hansky, of Pulkowa (whose recent death is deplored), introduced successfully a scheme of photography, which might almost be called a solar cinematograph. He took photographs of the sun at intervals of fifteen or thirty seconds, and then enlarged selected portions of these two hundred times, giving a picture corresponding to a solar disc of six metres diameter. In these enlarged pictures he was able to trace the movements, and changes of shape and brightness, of individual rice-grains. Some granules become larger or smaller. Some seem to rise out of a mist, as it were, and to become clearer. Others grow feebler. Some are split in two. Some are rotated through a right angle in a minute or less, although each of the grains may be the size of Great Britain. Generally they move together in groups of very various velocities, up to forty kilometres a second. These movements seem to have definite relation to any sun-spots in the neighbourhood. From the results already obtained it seems certain that, if this method of observation be continued, it cannot fail to supply facts of the greatest importance.

It is quite impossible to do justice here to the work of all those who are engaged on astronomical physics. The utmost that can be attempted is to give a fair idea of the directions of human thought and endeavour. During the last half-century America has made splendid progress, and an entirely new process of studying the photosphere has been independently perfected by Professor Hale at Chicago, and Deslandres at Paris.[8] They have succeeded in photographing the sun's surface in monochromatic light, such as the light given off as one of the bright lines of hydrogen or of calcium, by means of the "Spectroheliograph." The spectroscope is placed with its slit in the focus of an equatoreal telescope, pointed to the sun, so that the circular image of the sun falls on the slit. At the other end of the spectroscope is the photographic plate. Just in front of this plate there is another slit parallel to the first, in the position where the image of the first slit formed by the K line of calcium falls. Thus is obtained a photograph of the section of the sun, made by the first slit, only in K light. As the image of the sun passes over the first slit the photographic plate is moved at the same rate and in the same direction behind the second slit; and as successive sections of the

sun's image in the equatoreal enter the apparatus, so are these sections successively thrown in their proper place on the photographic plate, always in K light. By using a high dispersion the faculÃ which give off K light can be correctly photographed, not only at the sun's edge, but all over his surface. The actual mechanical method of carrying out the observation is not quite so simple as what is here described.

By choosing another line of the spectrum instead of calcium K–for example, the hydrogen line Hâââ–we obtain two photographs, one showing the appearance of the calcium floculi, and the other of the hydrogen floculi, on the same part of the solar surface; and nothing is more astonishing than to note the total want of resemblance in the forms shown on the two. This mode of research promises to afford many new and useful data.

The spectroscope has revealed the fact that, broadly speaking, the sun is composed of the same materials as the earth. Ãngstrom was the first to map out all of the lines to be found in the solar spectrum. But Rowland, of Baltimore, after having perfected the art of making true gratings with equidistant lines ruled on metal for producing spectra, then proceeded to make a map of the solar spectrum on a large scale.

In 1866 Lockyer[9] threw an image of the sun upon the slit of a spectroscope, and was thus enabled to compare the spectrum of a spot with that of the general solar surface. The observation proved the darkness of a spot to be caused by increased absorption of light, not only in the dark lines, which are widened, but over the entire spectrum. In 1883 Young resolved this continuous obscurity into an infinite number of fine lines, which have all been traced in a shadowy way on to the general solar surface. Lockyer also detected displacements of the spectrum lines in the spots, such as would be produced by a rapid motion in the line of sight. It has been found that both uprushes and downrushes occur, but there is no marked predominance of either in a sun-spot. The velocity of motion thus indicated in the line of sight sometimes appears to amount to 320 miles a second. But it must be remembered that pressure of a gas has some effect in displacing the spectral lines. So we must go on, collecting data, until a time comes when the meaning of all the facts can be made clear.

Total Solar Eclipses.–During total solar eclipses the time is so short, and the circumstances so impressive, that drawings of the appearance could not always be trusted. The red prominences of jagged form that are seen round the moon's edge, and the corona with its streamers radiating or interlacing, have much detail that can hardly be recorded in a sketch. By the aid of photography a number of records can be taken during the progress of totality. From a study of these the extent of the corona is demonstrated in one case to extend to at least six diameters of the moon, though the eye has traced it

farther. This corona is still one of the wonders of astronomy, and leads to many questions. What is its consistency, if it extends many million miles from the sun's surface? How is it that it opposed no resistance to the motion of comets which have almost grazed the sun's surface? Is this the origin of the zodiacal light? The character of the corona in photographic records has been shown to depend upon the phase of the sun-spot period. During the sun-spot maximum the corona seems most developed over the spot-zones–i.e., neither at the equator nor the poles. The four great sheaves of light give it a square appearance, and are made up of rays or plumes, delicate like the petals of a flower. During a minimum the nebulous ring seems to be made of tufts of fine hairs with aigrettes or radiations from both poles, and streamers from the equator.

[Illustration: SOLAR ECLIPSE, 1882. From drawing by W. H. Wesley, Secretary R.A.S.; showing the prominences, the corona, and an unknown comet.]

On September 19th, 1868, eclipse spectroscopy began with the Indian eclipse, in which all observers found that the red prominences showed a bright line spectrum, indicating the presence of hydrogen and other gases. So bright was it that Jansen exclaimed: "_Je verrai ces lignes-lÃ en dehors des Ãclipses_." And the next day he observed the lines at the edge of the uneclipsed sun. Huggins had suggested this observation in February, 1868, his idea being to use prisms of such great dispersive power that the continuous spectrum reflected by our atmosphere should be greatly weakened, while a bright line would suffer no diminution by the high dispersion. On October 20th Lockyer,[10] having news of the eclipse, but not of Jansen's observations the day after, was able to see these lines. This was a splendid performance, for it enabled the prominences to be observed, not only during eclipses, but every day. Moreover, the next year Huggins was able, by using a wide slit, to see the whole of a prominence and note its shape. Prominences are classified, according to their form, into "flame" and "cloud" prominences, the spectrum of the latter showing calcium, hydrogen, and helium; that of the former including a number of metals.

The D line of sodium is a double line, and in the same eclipse (1868) an orange line was noticed which was afterwards found to lie close to the two components of the D line. It did not correspond with any known terrestrial element, and the unknown element was called "helium." It was not until 1895 that Sir William Ramsay found this element as a gas in the mineral cleavite.

The spectrum of the corona is partly continuous, indicating light reflected from the sun's body. But it also shows a green line corresponding with no known terrestrial element, and the name "coronium" has been given to the substance causing it.

A vast number of facts have been added to our knowledge about the sun by photography and the spectroscope. Speculations and hypotheses in plenty have been offered, but it may be long before we have a complete theory evolved to explain all the phenomena of the storm-swept metallic atmosphere of the sun.

The proceedings of scientific societies teem with such facts and "working hypotheses," and the best of them have been collected by Miss Clerke in her _History of Astronomy during the Nineteenth Century_. As to established facts, we learn from the spectroscopic researches (1) that the continuous spectrum is derived from the _photosphere_ or solar gaseous material compressed almost to liquid consistency; (2) that the _reversing layer_ surrounds it and gives rise to black lines in the spectrum; that the _chromosphere_ surrounds this, is composed mainly of hydrogen, and is the cause of the red prominences in eclipses; and that the gaseous _corona_ surrounds all of these, and extends to vast distances outside the sun's visible surface.

FOOTNOTES:

[1] _Rosa Ursina_, by C. Scheiner, _fol_.; Bracciani, 1630.

[2] _R. S. Phil. Trans._, 1774.

[3] _Ibid_, 1783.

[4] _Observations on the Spots on the Sun, etc.,_ 4Â; London and Edinburgh, 1863.

[5] _PeriodicitÃt der Sonnenflecken. Astron. Nach. XXI._, 1844, P. 234.

[6] _R.S. Phil. Trans._ (ser. A), 1906, p. 69-100.

[7] "Researches on Solar Physics," by De la Rue, Stewart and Loewy; _R. S. Phil. Trans._, 1869, 1870.

[8] "The Sun as Photographed on the K line"; _Knowledge_, London, 1903, p. 229.

[9] _R. S. Proc._, xv., 1867, p. 256.

[10] _Acad. des Sc._, Paris; _C. R._, lxvii., 1868, p. 121.

13. THE MOON AND PLANETS.

The Moon.–Telescopic discoveries about the moon commence with Galileo's discovery that her surface has mountains and valleys, like the earth. He also found that, while she always turns the same face to

us, there is periodically a slight twist to let us see a little round the eastern or western edge. This was called _libration_, and the explanation was clear when it was understood that in showing always the same face to us she makes one revolution a month on her axis _uniformly_, and that her revolution round the earth is not uniform.

Galileo said that the mountains on the moon showed greater differences of level than those on the earth. ShrÃter supported this opinion. W. Herschel opposed it. But Beer and MÃdler measured the heights of lunar mountains by their shadows, and found four of them over 20,000 feet above the surrounding plains.

Langrenus [1] was the first to do serious work on selenography, and named the lunar features after eminent men. Riccioli also made lunar charts. In 1692 Cassini made a chart of the full moon. Since then we have the charts of SchrÃter, Beer and MÃdler (1837), and of Schmidt, of Athens (1878); and, above all, the photographic atlas by Loewy and Puiseux.

The details of the moon's surface require for their discussion a whole book, like that of Neison or the one by Nasmyth and Carpenter. Here a few words must suffice. Mountain ranges like our Andes or Himalayas are rare. Instead of that, we see an immense number of circular cavities, with rugged edges and flat interior, often with a cone in the centre, reminding one of instantaneous photographs of the splash of a drop of water falling into a pool. Many of these are fifty or sixty miles across, some more. They are generally spoken of as resembling craters of volcanoes, active or extinct, on the earth. But some of those who have most fully studied the shapes of craters deny altogether their resemblance to the circular objects on the moon. These so-called craters, in many parts, are seen to be closely grouped, especially in the snow-white parts of the moon. But there are great smooth dark spaces, like the clear black ice on a pond, more free from craters, to which the equally inappropriate name of seas has been given. The most conspicuous crater, _Tycho_, is near the south pole. At full moon there are seen to radiate from Tycho numerous streaks of light, or "rays," cutting through all the mountain formations, and extending over fully half the lunar disc, like the star-shaped cracks made on a sheet of ice by a blow. Similar cracks radiate from other large craters. It must be mentioned that these white rays are well seen only in full light of the sun at full moon, just as the white snow in the crevasses of a glacier is seen bright from a distance only when the sun is high, and disappears at sunset. Then there are deep, narrow, crooked "rills" which may have been water-courses; also "clefts" about half a mile wide, and often hundreds of miles long, like deep cracks in the surface going straight through mountain and valley.

The moon shares with the sun the advantage of being a good subject for

photography, though the planets are not. This is owing to her larger apparent size, and the abundance of illumination. The consequence is that the finest details of the moon, as seen in the largest telescope in the world, may be reproduced at a cost within the reach of all.

No certain changes have ever been observed; but several suspicions have been expressed, especially as to the small crater _LinnÃ_, in the _Mare Serenitatis_. It is now generally agreed that no certainty can be expected from drawings, and that for real evidence we must await the verdict of photography.

No trace of water or of an atmosphere has been found on the moon. It is possible that the temperature is too low. In any case, no displacement of a star by atmospheric refraction at occultation has been surely recorded. The moon seems to be dead.

The distance of the moon from the earth is just now the subject of re-measurement. The base line is from Greenwich to Cape of Good Hope, and the new feature introduced is the selection of a definite point on a crater (MÃsting A), instead of the moon's edge, as the point whose distance is to be measured.

The Inferior Planets.–When the telescope was invented, the phases of Venus attracted much attention; but the brightness of this planet, and her proximity to the sun, as with Mercury also, seemed to be a bar to the discovery of markings by which the axis and period of rotation could be fixed. Cassini gave the rotation as twenty-three hours, by observing a bright spot on her surface. ShrÃter made it 23h. 21m. 19s. This value was supported by others. In 1890 Schiaparelli[2] announced that Venus rotates, like our moon, once in one of her revolutions, and always directs the same face to the sun. This property has also been ascribed to Mercury; but in neither case has the evidence been generally accepted. Twenty-four hours is probably about the period of rotation for each of these planets.

Several observers have claimed to have seen a planet within the orbit of Mercury, either in transit over the sun's surface or during an eclipse. It has even been named _Vulcan_. These announcements would have received little attention but for the fact that the motion of Mercury has irregularities which have not been accounted for by known planets; and Le Verrier[3] has stated that an intra-Mercurial planet or ring of asteroids would account for the unexplained part of the motion of the line of apses of Mercury's orbit amounting to 38" per century.

Mars.–The first study of the appearance of Mars by Miraldi led him to believe that there were changes proceeding in the two white caps which are seen at the planet's poles. W. Herschel attributed these caps to ice and snow, and the dates of his observations indicated a melting of these ice-caps in the Martian summer.

SchrÃter attributed the other markings on Mars to drifting clouds. But Beer and MÃdler, in 1830-39, identified the same dark spots as being always in the same place, though sometimes blurred by mist in the local winter. A spot sketched by Huyghens in 1672, one frequently seen by W. Herschel in 1783, another by Arago in 1813, and nearly all the markings recorded by Beer and MÃdler in 1830, were seen and drawn by F. Kaiser in Leyden during seventeen nights of the opposition of 1862 (_Ast. Nacht._, No. 1,468), whence he deduced the period of rotation to be 24h. 37m. 22s.,62–or one-tenth of a second less than the period deduced by R. A. Proctor from a drawing by Hooke in 1666.

It must be noted that, if the periods of rotation both of Mercury and Venus be about twenty-four hours, as seems probable, all the four planets nearest to the sun rotate in the same period, while the great planets rotate in about ten hours (Uranus and Neptune being still indeterminate).

The general surface of Mars is a deep yellow; but there are dark grey or greenish patches. Sir John Herschel was the first to attribute the ruddy colour of Mars to its soil rather than to its atmosphere.

The observations of that keen-sighted observer Dawes led to the first good map of Mars, in 1869. In the 1877 opposition Schiaparelli revived interest in the planet by the discovery of canals, uniformly about sixty miles wide, running generally on great circles, some of them being three or four thousand miles long. During the opposition of 1881-2 the same observer re-observed the canals, and in twenty of them he found the canals duplicated,[4] the second canal being always 200 to 400 miles distant from its fellow.

The existence of these canals has been doubted. Mr. Lowell has now devoted years to the subject, has drawn them over and over again, and has photographed them; and accepts the explanation that they are artificial, and that vegetation grows on their banks. Thus is revived the old controversy between Whewell and Brewster as to the habitability of the planets. The new arguments are not yet generally accepted. Lowell believes he has, with the spectroscope, proved the existence of water on Mars.

One of the most unexpected and interesting of all telescopic discoveries took place in the opposition of 1877, when Mars was unusually near to the earth. The Washington Observatory had acquired the fine 26-inch refractor, and Asaph Hall searched for satellites, concealing the planet's disc to avoid the glare. On August 11th he had a suspicion of a satellite. This was confirmed on the 16th, and on the following night a second one was added. They are exceedingly faint, and can be seen only by the most powerful telescopes, and only at the times of opposition. Their diameters are estimated at six or seven miles. It was soon found that the first, Deimos, completes its orbit

in 30h. 18m. But the other, Phobos, at first was a puzzle, owing to its incredible velocity being unsuspected. Later it was found that the period of revolution was only 7h. 39m. 22s. Since the Martian day is twenty-four and a half hours, this leads to remarkable results. Obviously the easterly motion of the satellite overwhelms the diurnal rotation of the planet, and Phobos must appear to the inhabitants, if they exist, to rise in the west and set in the east, showing two or even three full moons in a day, so that, sufficiently well for the ordinary purposes of life, the hour of the day can be told by its phases.

The discovery of these two satellites is, perhaps, the most interesting telescopic visual discovery made with the large telescopes of the last half century; photography having been the means of discovering all the other new satellites except Jupiter's fifth (in order of discovery).

[Illustration: JUPITER. From a drawing by E. M. Antoniadi, showing transit of a satellite's shadow, the belts, and the "great red spot" (_Monthly Notices_, R. A. S., vol. lix., pl. x.).]

Jupiter.–Galileo's discovery of Jupiter's satellites was followed by the discovery of his belts. Zucchi and Torricelli seem to have seen them. Fontana, in 1633, reported three belts. In 1648 Grimaldi saw but two, and noticed that they lay parallel to the ecliptic. Dusky spots were also noticed as transient. Hooke[5] measured the motion of one in 1664. In 1665 Cassini, with a fine telescope, 35-feet focal length, observed many spots moving from east to west, whence he concluded that Jupiter rotates on an axis like the earth. He watched an unusually permanent spot during twenty-nine rotations, and fixed the period at 9h. 56m. Later he inferred that spots near the equator rotate quicker than those in higher latitudes (the same as Carrington found for the sun); and W. Herschel confirmed this in 1778-9.

Jupiter's rapid rotation ought, according to Newton's theory, to be accompanied by a great flattening at the poles. Cassini had noted an oval form in 1691. This was confirmed by La Hire, RÃmer, and Picard. Pound measured the ellipticity = 1/(13.25).

W. Herschel supposed the spots to be masses of cloud in the atmosphere–an opinion still accepted. Many of them were very permanent. Cassini's great spot vanished and reappeared nine times between 1665 and 1713. It was close to the northern margin of the southern belt. Herschel supposed the belts to be the body of the planet, and the lighter parts to be clouds confined to certain latitudes.

In 1665 Cassini observed transits of the four satellites, and also saw their shadows on the planet, and worked out a lunar theory for Jupiter. Mathematical astronomers have taken great interest in the

perturbations of the satellites, because their relative periods introduce peculiar effects. Airy, in his delightful book, _Gravitation_, has reduced these investigations to simple geometrical explanations.

In 1707 and 1713 Miraldi noticed that the fourth satellite varies much in brightness. W. Herschel found this variation to depend upon its position in its orbit, and concluded that in the positions of feebleness it is always presenting to us a portion of its surface, which does not well reflect the sun's light; proving that it always turns the same face to Jupiter, as is the case with our moon. This fact had also been established for Saturn's fifth satellite, and may be true for all satellites.

In 1826 Struve measured the diameters of the four satellites, and found them to be 2,429, 2,180, 3,561, and 3,046 miles.

In modern times much interest has been taken in watching a rival to Cassini's famous spot. The "great red spot" was first observed by Niesten, Pritchett, and Tempel, in 1878, as a rosy cloud attached to a whitish zone beneath the dark southern equatorial band, shaped like the new war balloons, 30,000 miles long and 7,000 miles across. The next year it was brick-red. A white spot beside it completed a rotation in less time by 5Â minutes than the red spot–a difference of 260 miles an hour. Thus they came together again every six weeks, but the motions did not continue uniform. The spot was feeble in 1882-4, brightened in 1886, and, after many changes, is still visible.

Galileo's great discovery of Jupiter's four moons was the last word in this connection until September 9th, 1892, when Barnard, using the 36-inch refractor of the Lick Observatory, detected a tiny spot of light closely following the planet. This proved to be a new satellite (fifth), nearer to the planet than any other, and revolving round it in 11h. 57m. 23s. Between its rising and setting there must be an interval of 2Â Jovian days, and two or three full moons. The sixth and seventh satellites were found by the examination of photographic plates at the Lick Observatory in 1905, since which time they have been continuously photographed, and their orbits traced, at Greenwich. On examining these plates in 1908 Mr. Melotte detected the eighth satellite, which seems to be revolving in a retrograde orbit three times as far from its planet as the next one (seventh), in these two points agreeing with the outermost of Saturn's satellites (Phoebe).

Saturn.–This planet, with its marvellous ring, was perhaps the most wonderful object of those first examined by Galileo's telescope. He was followed by Dominique Cassini, who detected bands like Jupiter's belts. Herschel established the rotation of the planet in 1775-94. From observations during one hundred rotations he found the period to be 10h. 16m. 0s., 44. Herschel also measured the ratio of the polar to the equatoreal diameter as 10:11.

The ring was a complete puzzle to Galileo, most of all when the planet reached a position where the plane of the ring was in line with the earth, and the ring disappeared (December 4th, 1612). It was not until 1656 that Huyghens, in his small pamphlet _De Saturni Luna Observatio Nova_, was able to suggest in a cypher the ring form; and in 1659, in his Systema Saturnium, he gave his reasons and translated the cypher: "The planet is surrounded by a slender flat ring, everywhere distinct from its surface, and inclined to the ecliptic." This theory explained all the phases of the ring which had puzzled others. This ring was then, and has remained ever since, a unique structure. We in this age have got accustomed to it. But Huyghens's discovery was received with amazement.

In 1675 Cassini found the ring to be double, the concentric rings being separated by a black band–a fact which was placed beyond dispute by Herschel, who also found that the thickness of the ring subtends an angle less than 0".3. ShrÃter estimated its thickness at 500 miles.

Many speculations have been advanced to explain the origin and constitution of the ring. De Sejour said [6] that it was thrown off from Saturn's equator as a liquid ring, and afterwards solidified. He noticed that the outside would have a greater velocity, and be less attracted to the planet, than the inner parts, and that equilibrium would be impossible; so he supposed it to have solidified into a number of concentric rings, the exterior ones having the least velocity.

Clerk Maxwell, in the Adams prize essay, gave a physico-mathematical demonstration that the rings must be composed of meteoritic matter like gravel. Even so, there must be collisions absorbing the energy of rotation, and tending to make the rings eventually fall into the planet. The slower motion of the external parts has been proved by the spectroscope in Keeler's hands, 1895.

Saturn has perhaps received more than its share of attention owing to these rings. This led to other discoveries. Huyghens in 1655, and J. D. Cassini in 1671, discovered the sixth and eighth satellites (Titan and Japetus). Cassini lost his satellite, and in searching for it found Rhea (the fifth) in 1672, besides his old friend, whom he lost again. He added the third and fourth in 1684 (Tethys and Dione). The first and second (Mimas and Encelades) were added by Herschel in 1789, and the seventh (Hyperion) simultaneously by Lassel and Bond in 1848. The ninth (Phoebe) was found on photographs, by Pickering in 1898, with retrograde motion; and he has lately added a tenth.

The occasional disappearance of Cassini's Japetus was found on investigation to be due to the same causes as that of Jupiter's fourth

satellite, and proves that it always turns the same face to the planet.

Uranus and Neptune.–The splendid discoveries of Uranus and two satellites by Sir William Herschel in 1787, and of Neptune by Adams and Le Verrier in 1846, have been already described. Lassel added two more satellites to Uranus in 1851, and found Neptune's satellite in 1846. All of the satellites of Uranus have retrograde motion, and their orbits are inclined about 80Â to the ecliptic.

The spectroscope has shown the existence of an absorbing atmosphere on Jupiter and Saturn, and there are suspicions that they partake something of the character of the sun, and emit some light besides reflecting solar light. On both planets some absorption lines seem to agree with the aqueous vapour lines of our own atmosphere; while one, which is a strong band in the red common to both planets, seems to agree with a line in the spectrum of some reddish stars.

Uranus and Neptune are difficult to observe spectroscopically, but appear to have peculiar spectra agreeing together. Sometimes Uranus shows Frauenhofer lines, indicating reflected solar light. But generally these are not seen, and six broad bands of absorption appear. One is the F. of hydrogen; another is the red-star line of Jupiter and Saturn. Neptune is a very difficult object for the spectroscope.

Quite lately [7] P. Lowell has announced that V. M. Slipher, at Flagstaff Observatory, succeeded in 1907 in rendering some plates sensitive far into the red. A reproduction is given of photographed spectra of the four outermost planets, showing (1) a great number of new lines and bands; (2) intensification of hydrogen F. and C. lines; (3) a steady increase of effects (1) and (2) as we pass from Jupiter and Saturn to Uranus, and a still greater increase in Neptune.

Asteroids.–The discovery of these new planets has been described. At the beginning of the last century it was an immense triumph to catch a new one. Since photography was called into the service by Wolf, they have been caught every year in shoals. It is like the difference between sea fishing with the line and using a steam trawler. In the 1908 almanacs nearly seven hundred asteroids are included. The computation of their perturbations and ephemerides by Euler's and Lagrange's method of variable elements became so laborious that Encke devised a special process for these, which can be applied to many other disturbed orbits. [8]

When a photograph is taken of a region of the heavens including an asteroid, the stars are photographed as points because the telescope is made to follow their motion; but the asteroids, by their proper motion, appear as short lines.

The discovery of Eros and the photographic attack upon its path have been described in their relation to finding the sun's distance.

A group of four asteroids has lately been found, with a mean distance and period equal to that of Jupiter. To three of these masculine names have been given–Hector, Patroclus, Achilles; the other has not yet been named.

FOOTNOTES:

[1] Langrenus (van Langren), F. Selenographia sive lumina austriae philippica; Bruxelles, 1645.

[2] _Astr. Nach._, 2,944.

[3] _Acad. des Sc._, Paris; _C.R._, lxxxiii., 1876.

[4] _Mem. Spettr. Ital._, xi., p. 28.

[5] _R. S. Phil. Trans_., No. 1.

[6] Grant's _Hist. Ph. Ast_., p. 267.

[7] _Nature_, November 12th, 1908.

[8] _Ast. Nach_., Nos. 791, 792, 814, translated by G. B. Airy. _Naut. Alm_., Appendix, 1856.

14. COMETS AND METEORS.

Ever since Halley discovered that the comet of 1682 was a member of the solar system, these wonderful objects have had a new interest for astronomers; and a comparison of orbits has often identified the return of a comet, and led to the detection of an elliptic orbit where the difference from a parabola was imperceptible in the small portion of the orbit visible to us. A remarkable case in point was the comet of 1556, of whose identity with the comet of 1264 there could be little doubt. Hind wanted to compute the orbit more exactly than Halley had done. He knew that observations had been made, but they were lost. Having expressed his desire for a search, all the observations of Fabricius and of Heller, and also a map of the comet's path among the stars, were eventually unearthed in the most unlikely manner, after being lost nearly three hundred years. Hind and others were certain that this comet would return between 1844 and 1848, but it never appeared.

When the spectroscope was first applied to finding the composition of the heavenly bodies, there was a great desire to find out what comets are made of. The first opportunity came in 1864, when Donati observed the spectrum of a comet, and saw three bright bands, thus proving that

it was a gas and at least partly self-luminous. In 1868 Huggins compared the spectrum of Winnecke's comet with that of a Geissler tube containing olefiant gas, and found exact agreement. Nearly all comets have shown the same spectrum.[1] A very few comets have given bright band spectra differing from the normal type. Also a certain kind of continuous spectrum, as well as reflected solar light showing Frauenhofer lines, have been seen.

[Illustration: COPY OF THE DRAWING MADE BY PAUL FABRICIUS. To define
the path of comet 1556. After being lost for 300 years, this drawing was recovered by the prolonged efforts of Mr. Hind and Professor Littrow in 1856.]

When Wells's comet, in 1882, approached very close indeed to the sun, the spectrum changed to a mono-chromatic yellow colour, due to sodium.

For a full account of the wonders of the cometary world the reader is referred to books on descriptive astronomy, or to monographs on comets.[2] Nor can the very uncertain speculations about the structure of comets' tails be given here. A new explanation has been proposed almost every time that a great discovery has been made in the theory of light, heat, chemistry, or electricity.

Halley's comet remained the only one of which a prediction of the return had been confirmed, until the orbit of the small, ill-defined comet found by Pons in 1819 was computed by Encke, and found to have a period of 3â years. It was predicted to return in 1822, and was recognised by him as identical with many previous comets. This comet, called after Encke, has showed in each of its returns an inexplicable reduction of mean distance, which led to the assertion of a resisting medium in space until a better explanation could be found.[3]

Since that date fourteen comets have been found with elliptic orbits, whose aphelion distances are all about the same as Jupiter's mean distance; and six have an aphelion distance about ten per cent, greater than Neptune's mean distance. Other comets are similarly associated with the planets Saturn and Uranus.

The physical transformations of comets are among the most wonderful of unexplained phenomena in the heavens. But, for physical astronomers, the greatest interest attaches to the reduction of radius vector of Encke's comet, the splitting of Biela's comet into two comets in 1846, and the somewhat similar behaviour of other comets. It must be noted, however, that comets have a sensible size, that all their parts cannot travel in exactly the same orbit under the sun's gravitation, and that their mass is not sufficient to retain the parts together very forcibly; also that the inevitable collision of particles, or else fluid friction, is absorbing energy, and so reducing the comet's velocity.

In 1770 Lexell discovered a comet which, as was afterwards proved by investigations of Lexell, Burchardt, and Laplace, had in 1767 been deflected by Jupiter out of an orbit in which it was invisible from the earth into an orbit with a period of 5Â years, enabling it to be seen. In 1779 it again approached Jupiter closer than some of his satellites, and was sent off in another orbit, never to be again recognised.

But our interest in cometary orbits has been added to by the discovery that, owing to the causes just cited, a comet, if it does not separate into discrete parts like Biela's, must in time have its parts spread out so as to cover a sensible part of the orbit, and that, when the earth passes through such part of a comet's orbit, a meteor shower is the result.

A magnificent meteor shower was seen in America on November 12th-13th, 1833, when the paths of the meteors all seemed to radiate from a point in the constellation Leo. A similar display had been witnessed in Mexico by Humboldt and Bonpland on November 12th, 1799. H. A. Newton traced such records back to October 13th, A.D. 902. The orbital motion of a cloud or stream of small particles was indicated. The period favoured by H. A. Newton was 354Â days; another suggestion was 375Â days, and another 33Â years. He noticed that the advance of the date of the shower between 902 and 1833, at the rate of one day in seventy years, meant a progression of the node of the orbit. Adams undertook to calculate what the amount would be on all the five suppositions that had been made about the period. After a laborious work, he found that none gave one day in seventy years except the 33Â-year period, which did so exactly. H. A. Newton predicted a return of the shower on the night of November 13th-14th, 1866. He is now dead; but many of us are alive to recall the wonder and enthusiasm with which we saw this prediction being fulfilled by the grandest display of meteors ever seen by anyone now alive.

The _progression_ of the nodes proved the path of the meteor stream to be retrograde. The _radiant_ had almost the exact longitude of the point towards which the earth was moving. This proved that the meteor cluster was at perihelion. The period being known, the eccentricity of the orbit was obtainable, also the orbital velocity of the meteors in perihelion; and, by comparing this with the earth's velocity, the latitude of the radiant enabled the inclination to be determined, while the longitude of the earth that night was the longitude of the node. In such a way Schiaparelli was able to find first the elements of the orbit of the August meteor shower (Perseids), and to show its identity with the orbit of Tuttle's comet 1862.iii. Then, in January 1867, Le Verrier gave the elements of the November meteor shower (Leonids); and Peters, of Altona, identified these with Oppolzer's elements for Tempel's comet 1866–Schiaparelli having independently attained both of these results. Subsequently

Weiss, of Vienna, identified the meteor shower of April 20th (Lyrids) with comet 1861. Finally, that indefatigable worker on meteors, A. S. Herschel, added to the number, and in 1878 gave a list of seventy-six coincidences between cometary and meteoric orbits.

Cometary astronomy is now largely indebted to photography, not merely for accurate delineations of shape, but actually for the discovery of most of them. The art has also been applied to the observation of comets at distances from their perihelia so great as to prevent their visual observation. Thus has Wolf, of Heidelburg, found upon old plates the position of comet 1905.v., as a star of the 15.5 magnitude, 783 days before the date of its discovery. From the point of view of the importance of finding out the divergence of a cometary orbit from a parabola, its period, and its aphelion distance, this increase of range attains the very highest value.

The present Astronomer Royal, appreciating this possibility, has been searching by photography for Halley's comet since November, 1907, although its perihelion passage will not take place until April, 1910.

FOOTNOTES:

[1] In 1874, when the writer was crossing the Pacific Ocean in H.M.S. "Scout," Coggia's comet unexpectedly appeared, and (while Colonel Tupman got its positions with the sextant) he tried to use the prism out of a portable direct-vision spectroscope, without success until it was put in front of the object-glass of a binocular, when, to his great joy, the three band images were clearly seen.

[2] Such as _The World of Comets_, by A. Guillemin; _History of Comets_, by G. R. Hind, London, 1859; _Theatrum Cometicum_, by S. de Lubienietz, 1667; _Cometographie_, by PingrÃ, Paris, 1783; _Donati's Comet_, by Bond.

[3] The investigations by Von Asten (of St. Petersburg) seem to support, and later ones, especially those by Backlund (also of St. Petersburg), seem to discredit, the idea of a resisting medium.

15. THE FIXED STARS AND NEBUL.

Passing now from our solar system, which appears to be subject to the action of the same forces as those we experience on our globe, there remains an innumerable host of fixed stars, nebulas, and nebulous clusters of stars. To these the attention of astronomers has been more earnestly directed since telescopes have been so much enlarged. Photography also has enabled a vast amount of work to be covered in a comparatively short period, and the spectroscope has given them the means, not only of studying the chemistry of the heavens, but also of detecting any motion in the line of sight from less than a mile a second and upwards in any star, however distant, provided it be bright

enough.

[Illustration: SIR WILLIAM HERSCHEL, F.R.S.–1738-1822. Painted by Lemuel F. Abbott; National Portrait Gallery, Room XX.]

In the field of telescopic discovery beyond our solar system there is no one who has enlarged our knowledge so much as Sir William Herschel, to whom we owe the greatest discovery in dynamical astronomy among the stars–viz., that the law of gravitation extends to the most distant stars, and that many of them describe elliptic orbits about each other. W. Herschel was born at Hanover in 1738, came to England in 1758 as a trained musician, and died in 1822. He studied science when he could, and hired a telescope, until he learnt to make his own specula and telescopes. He made 430 parabolic specula in twenty-one years. He discovered 2,500 nebulÃ and 806 double stars, counted the stars in 3,400 guage-fields, and compared the principal stars photometrically.

Some of the things for which he is best known were results of those accidents that happen only to the indefatigable enthusiast. Such was the discovery of Uranus, which led to funds being provided for constructing his 40-feet telescope, after which, in 1786, he settled at Slough. In the same way, while trying to detect the annual parallax of the stars, he failed in that quest, but discovered binary systems of stars revolving in ellipses round each other; just as Bradley's attack on stellar parallax failed, but led to the discovery of aberration, nutation, and the true velocity of light.

Parallax.–The absence of stellar parallax was the great objection to any theory of the earth's motion prior to Kepler's time. It is true that Kepler's theory itself could have been geometrically expressed equally well with the earth or any other point fixed. But in Kepler's case the obviously implied physical theory of the planetary motions, even before Newton explained the simplicity of conception involved, made astronomers quite ready to waive the claim for a rigid proof of the earth's motion by measurement of an annual parallax of stars, which they had insisted on in respect of Copernicus's revival of the idea of the earth's orbital motion.

Still, the desire to measure this parallax was only intensified by the practical certainty of its existence, and by repeated failures. The attempts of Bradley failed. The attempts of Piazzi and Brinkley,[1] early in the nineteenth century, also failed. The first successes, afterwards confirmed, were by Bessel and Henderson. Both used stars whose proper motion had been found to be large, as this argued proximity. Henderson, at the Cape of Good Hope, observed Î± Centauri, whose annual proper motion he found to amount to 3".6, in 1832-3; and a few years later deduced its parallax 1".16. His successor at the Cape, Maclear, reduced this to 0".92.

In 1835 Struve assigned a doubtful parallax of 0".261 to Vega (Îł LyrÃ). But Bessel's observations, between 1837 and 1840, of 61 Cygni, a star with the large proper motion of over 5", established its annual parallax to be 0".3483; and this was confirmed by Peters, who found the value 0".349.

Later determinations for Îłâ Centauri, by Gill,[2] make its parallax 0".75–This is the nearest known fixed star; and its light takes 4â years to reach us. The light year is taken as the unit of measurement in the starry heavens, as the earth's mean distance is "the astronomical unit" for the solar system.[3] The proper motions and parallaxes combined tell us the velocity of the motion of these stars across the line of sight: Îł Centauri 14.4 miles a second=4.2 astronomical units a year; 61 Cygni 37.9 miles a second=11.2 astronomical units a year. These successes led to renewed zeal, and now the distances of many stars are known more or less accurately.

Several of the brightest stars, which might be expected to be the nearest, have not shown a parallax amounting to a twentieth of a second of arc. Among these are Canopus, Îł Orionis, Îł Cygni, Î Centauri, and Î Cassiopeia. Oudemans has published a list of parallaxes observed.[4]

Proper Motion.–In 1718 Halley[5] detected the proper motions of Arcturus and Sirius. In 1738 J. Cassinis[6] showed that the former had moved five minutes of arc since Tycho Brahe fixed its position. In 1792 Piazzi noted the motion of 61 Cygni as given above. For a long time the greatest observed proper motion was that of a small star 1830 Groombridge, nearly 7" a year; but others have since been found reaching as much as 10".

Now the spectroscope enables the motion of stars to be detected at a single observation, but only that part of the motion that is in the line of sight. For a complete knowledge of a star's motion the proper motion and parallax must also be known.

When Huggins first applied the Doppler principle to measure velocities in the line of sight,[7] the faintness of star spectra diminished the accuracy; but VÃgel, in 1888, overcame this to a great extent by long exposures of photographic plates.

It has often been noticed that stars which seem to belong to a group of nearly uniform magnitude have the same proper motion. The spectroscope has shown that these have also often the same velocity in the line of sight. Thus in the Great Bear, Î, Î, Î, Î, Î, all agree as to angular proper motion. Î was too faint for a spectroscopic measurement, but all the others have been shown to be approaching us at a rate of twelve to twenty miles a second. The same has been proved for proper motion, and line of sight motion, in the case of Pleiades and other groups.

Maskelyne measured many proper motions of stars, from which W. Herschel[8] came to the conclusion that these apparent motions are for the most part due to a motion of the solar system in space towards a point in the constellation Hercules, R.A. 257Â; N. Decl. 25Â. This grand discovery has been amply confirmed, and, though opinions differ as to the exact direction, it happens that the point first indicated by Herschel, from totally insufficient data, agrees well with modern estimates.

Comparing the proper motions and parallaxes to get the actual velocity of each star relative to our system, C.L. Struve found the probable velocity of the solar system in space to be fifteen miles a second, or five astronomical units a year.

The work of Herschel in this matter has been checked by comparing spectroscopic velocities in the line of sight which, so far as the sun's motion is concerned, would give a maximum rate of approach for stars near Hercules, a maximum rate of recession for stars in the opposite part of the heavens, and no effect for stars half-way between. In this way the spectroscope has confirmed generally Herschel's view of the direction, and makes the velocity eleven miles a second, or nearly four astronomical units a year.

The average proper motion of a first magnitude star has been found to be 0".25 annually, and of a sixth magnitude star 0".04. But that all bright stars are nearer than all small stars, or that they show greater proper motion for that reason, is found to be far from the truth. Many statistical studies have been made in this connection, and interesting results may be expected from this treatment in the hands of Kapteyn of Groningen, and others.[9]

On analysis of the directions of proper motions of stars in all parts of the heavens, Kapteyn has shown[10] that these indicate, besides the solar motion towards Hercules, two general drifts of stars in nearly opposite directions, which can be detected in any part of the heavens. This result has been confirmed from independent data by Eddington (_R.A.S., M.N._) and Dyson (_R.S.E. Proc._).

Photography promises to assist in the measurement of parallax and proper motions. Herr Pulfrich, of the firm of Carl Zeiss, has vastly extended the applications of stereoscopic vision to astronomy–a subject which De la Rue took up in the early days of photography. He has made a stereo-comparator of great beauty and convenience for comparing stereoscopically two star photographs taken at different dates. Wolf of Heidelberg has used this for many purposes. His investigations depending on the solar motion in space are remarkable. He photographs stars in a direction at right angles to the line of the sun's motion. He has taken photographs of the same region fourteen years apart, the two positions of his camera being at the two ends of

a base-line over 5,000,000,000 miles apart, or fifty-six astronomical units. On examining these stereoscopically, some of the stars rise out of the general plane of the stars, and seem to be much nearer. Many of the stars are thus seen to be suspended in space at different distances corresponding exactly to their real distances from our solar system, except when their proper motion interferes. The effect is most striking; the accuracy of measurement exceeds that of any other method of measuring such displacements, and it seems that with a long interval of time the advantage of the method increases.

Double Stars.–The large class of double stars has always been much studied by amateurs, partly for their beauty and colour, and partly as a test for telescopic definition. Among the many unexplained stellar problems there is one noticed in double stars that is thought by some to be likely to throw light on stellar evolution. It is this: There are many instances where one star of the pair is comparatively faint, and the two stars are contrasted in colour; and in every single case the general colour of the faint companion is invariably to be classed with colours more near to the blue end of the spectrum than that of the principal star.

Binary Stars.–Sir William Herschel began his observations of double stars in the hope of discovering an annual parallax of the stars. In this he was following a suggestion of Galileo's. The presumption is that, if there be no physical connection between the stars of a pair, the largest is the nearest, and has the greatest parallax. So, by noting the distance between the pair at different times of the year, a delicate test of parallax is provided, unaffected by major instrumental errors.

Herschel did, indeed, discover changes of distance, but not of the character to indicate parallax. Following this by further observation, he found that the motions were not uniform nor rectilinear, and by a clear analysis of the movements he established the remarkable and wholly unexpected fact that in all these cases the motion is due to a revolution about their common centre of gravity.[11] He gave the approximate period of revolution of some of these: Castor, 342 years; Î Serpentis, 375 years; Î Leonis, 1,200 years; Î Bootis, 1,681 years.

Twenty years later Sir John Herschel and Sir James South, after re-examination of these stars, confirmed[12] and extended the results, one pair of CoronÃ having in the interval completed more than a whole revolution.

It is, then, to Sir William Herschel that we owe the extension of the law of gravitation, beyond the limits of the solar system, to the whole universe. His observations were confirmed by F.G.W. Struve (born 1793, died 1864), who carried on the work at Dorpat. But it was first to Savary,[13] and later to Encke and Sir John Herschel, that we owe the computation of the elliptic elements of these stars; also the

resulting identification of their law of force with Newton's force of gravitation applied to the solar system, and the force that makes an apple fall to the ground. As Grant well says in his _History_: "This may be justly asserted to be one of the most sublime truths which astronomical science has hitherto disclosed to the researches of the human mind."

Latterly the best work on double stars has been done by S. W. Burnham,[14] at the Lick Observatory. The shortest period he found was eleven years (Î Pegasi). In the case of some of these binaries the parallax has been measured, from which it appears that in four of the surest cases the orbits are about the size of the orbit of Uranus, these being probably among the smallest stellar orbits.

The law of gravitation having been proved to extend to the stars, a discovery (like that of Neptune in its origin, though unlike it in the labour and originality involved in the calculation) that entrances the imagination became possible, and was realised by Bessel–the discovery of an unknown body by its gravitational disturbance on one that was visible. In 1834 and 1840 he began to suspect a want of uniformity in the proper motion of Sirius and Procyon respectively. In 1844, in a letter to Sir John Herschel,[15] he attributed these irregularities in each case to the attraction of an invisible companion, the period of revolution of Sirius being about half a century. Later he said: "I adhere to the conviction that Procyon and Sirius form real binary systems, consisting of a visible and an invisible star. There is no reason to suppose luminosity an essential quality of cosmical bodies. The visibility of countless stars is no argument against the invisibility of countless others." This grand conception led Peters to compute more accurately the orbit, and to assign the place of the invisible companion of Sirius. In 1862 Alvan G. Clark was testing a new 18-inch object-glass (now at Chicago) upon Sirius, and, knowing nothing of these predictions, actually found the companion in the very place assigned to it. In 1896 the companion of Procyon was discovered by Professor Schaeberle at the Lick Observatory.

Now, by the refined parallax determinations of Gill at the Cape, we know that of Sirius to be 0".38. From this it has been calculated that the mass of Sirius equals two of our suns, and its intrinsic brightness equals twenty suns; but the companion, having a mass equal to our sun, has only a five-hundredth part of the sun's brightness.

Spectroscopic Binaries.–On measuring the velocity of a star in the line of sight at frequent intervals, periodic variations have been found, leading to a belief in motion round an invisible companion. Vogel, in 1889, discovered this in the case of Spica (Îł Virginis), whose period is 4d. 0h. 19m., and the diameter of whose orbit is six million miles. Great numbers of binaries of this type have since then been discovered, all of short period.

Also, in 1889, Pickering found that at regular intervals of fifty-two days the lines in the spectrum of Î of the Great Bear are duplicated, indicating a relative velocity, equal to one hundred miles a second, of two components revolving round each other, of which that apparently single star must be composed.

It would be interesting, no doubt, to follow in detail the accumulating knowledge about the distances, proper motions, and orbits of the stars; but this must be done elsewhere. Enough has been said to show how results are accumulating which must in time unfold to us the various stellar systems and their mutual relationships.

Variable Stars.–It has often happened in the history of different branches of physical science that observation and experiment were so far ahead of theory that hopeless confusion appeared to reign; and then one chance result has given a clue, and from that time all differences and difficulties in the previous researches have stood forth as natural consequences, explaining one another in a rational sequence. So we find parallax, proper motion, double stars, binary systems, variable stars, and new stars all bound together.

The logical and necessary explanation given of the cause of ordinary spectroscopic binaries, and of irregular proper motions of Sirius and Procyon, leads to the inference that if ever the plane of such a binary orbit were edge-on to us there ought to be an eclipse of the luminous partner whenever the non-luminous one is interposed between us. This should give rise either to intermittence in the star's light or else to variability. It was by supposing the existence of a dark companion to Algol that its discoverer, Goodricke of York,[16] in 1783, explained variable stars of this type. Algol (Î Persei) completes the period of variable brightness in 68.8 hours. It loses three-fifths of its light, and regains it in twelve hours. In 1889 Vogel,[17] with the Potsdam spectrograph, actually found that the luminous star is receding before each eclipse, and approaching us after each eclipse; thus entirely supporting Goodricke's opinion. There are many variables of the Algol type, and information is steadily accumulating. But all variable stars do not suffer the sudden variations of Algol. There are many types, and the explanations of others have not proved so easy.

The Harvard College photographs have disclosed the very great prevalence of variability, and this is certainly one of the lines in which modern discovery must progress.

Roberts, in South Africa, has done splendid work on the periods of variables of the Algol type.

New Stars.–Extreme instances of variable stars are the new stars such as those detected by Hipparchus, Tycho Brahe, and Kepler, of

which many have been found in the last half-century. One of the latest great "NovÃ" was discovered in Auriga by a Scotsman, Dr. Anderson, on February 1st, 1892, and, with the modesty of his race, he communicated the fact to His Majesty's Astronomer for Scotland on an unsigned post-card.[18] Its spectrum was observed and photographed by Huggins and many others. It was full of bright lines of hydrogen, calcium, helium, and others not identified. The astounding fact was that lines were shown in pairs, bright and dark, on a faint continuous spectrum, indicating apparently that a dark body approaching us at the rate of 550 miles a second[19] was traversing a cold nebulous atmosphere, and was heated to incandescence by friction, like a meteor in our atmosphere, leaving a luminous train behind it. It almost disappeared, and on April 26th it was of the sixteenth magnitude; but on August 17th it brightened to the tenth, showing the principal nebular band in its spectrum, and no sign of approach or recession. It was as if it emerged from one part of the nebula, cooled down, and rushed through another part of the nebula, rendering the nebular gas more luminous than itself.[20]

Since 1892 one Nova after another has shown a spectrum as described above, like a meteor rushing towards us and leaving a train behind, for this seems to be the obvious meaning of the spectra.

The same may be said of the brilliant Nova Persei, brighter at its best than Capella, and discovered also by Dr. Anderson on February 22nd, 1901. It increased in brightness as it reached the densest part of the nebula, then it varied for some weeks by a couple of magnitudes, up and down, as if passing through separate nebular condensations. In February, 1902, it could still be seen with an opera-glass. As with the other NovÃ, when it first dashed into the nebula it was vaporised and gave a continuous spectrum with dark lines of hydrogen and helium. It showed no bright lines paired with the dark ones to indicate a train left behind; but in the end its own luminosity died out, and the nebular spectrum predominated.

The nebular illumination as seen in photographs, taken from August to November, seemed to spread out slowly in a gradually increasing circle at the rate of 90" in forty-eight days. Kapteyn put this down to the velocity of light, the original outburst sending its illumination to the nebulous gas and illuminating a spherical shell whose radius increased at the velocity of light. This supposition seems correct, in which case it can easily be shown from the above figures that the distance of this Nova was 300 light years.

Star Catalogues.–Since the days of very accurate observations numerous star-catalogues have been produced by individuals or by observatories. Bradley's monumental work may be said to head the list. Lacaille's, in the Southern hemisphere, was complementary. Then Piazzi, Lalande, Groombridge, and Bessel were followed by Argelander with his 324,000 stars, Rumker's Paramatta catalogue of the southern

hemisphere, and the frequent catalogues of national observatories. Later the Astronomische Gesellschaft started their great catalogue, the combined work of many observatories. Other southern ones were Gould's at Cordova and Stone's at the Cape.

After this we have a new departure. Gill at the Cape, having the comet 1882.ii. all to himself in those latitudes, wished his friends in Europe to see it, and employed a local photographer to strap his camera to the observatory equatoreal, driven by clockwork, and adjusted on the comet by the eye. The result with half-an-hour's exposure was good, so he tried three hours. The result was such a display of sharp star images that he resolved on the Cape Photographic Durchmusterung, which after fourteen years, with Kapteyn's aid in reducing, was completed. Meanwhile the brothers Henry, of Paris, were engaged in going over Chacornac's zodiacal stars, and were about to catalogue the Milky Way portion, a serious labour, when they saw Gill's Comet photograph and conceived the idea of doing the rest of their work by photography. Gill had previously written to Admiral Mouchez, of the Paris Observatory, and explained to him his project for charting the heavens photographically, by combining the work of many observatories. This led Admiral Mouchez to support the brothers Henry in their scheme.[21] Gill, having got his own photographic work underway, suggested an international astrographic chart, the materials for different zones to be supplied by observatories of all nations, each equipped with similar photographic telescopes. At a conference in Paris, 1887, this was decided on, the stars on the charts going down to the fourteenth magnitude, and the catalogues to the eleventh.

[Illustration: GREAT COMET, Nov. 14TH, 1882. (Exposure 2hrs. 20m.) By
kind permission of Sir David Gill. From this photograph originated all stellar chart-photography.]

This monumental work is nearing completion. The labour involved was immense, and the highest skill was required for devising instruments and methods to read off the star positions from the plates.

Then we have the Harvard College collection of photographic plates, always being automatically added to; and their annex at Arequipa in Peru.

Such catalogues vary in their degree of accuracy; and fundamental catalogues of standard stars have been compiled. These require extension, because the differential methods of the heliometer and the camera cannot otherwise be made absolute.

The number of stars down to the fourteenth magnitude may be taken at about 30,000,000; and that of all the stars visible in the greatest modern telescopes is probably about 100,000,000.

NebulÃ and Star-clusters.–Our knowledge of nebulÃ really dates from the time of W. Herschel. In his great sweeps of the heavens with his giant telescopes he opened in this direction a new branch of astronomy. At one time he held that all nebulÃ might be clusters of innumerable minute stars at a great distance. Then he recognised the different classes of nebulÃ, and became convinced that there is a widely-diffused "shining fluid" in space, though many so-called nebulÃ could be resolved by large telescopes into stars. He considered that the Milky Way is a great star cluster, whose form may be conjectured from numerous star-gaugings. He supposed that the compact "planetary nebulÃ" might show a stage of evolution from the diffuse nebulÃ, and that his classifications actually indicate various stages of development. Such speculations, like those of the ancients about the solar system, are apt to be harmful to true progress of knowledge unless in the hands of the ablest mathematical physicists; and Herschel violated their principles in other directions. But here his speculations have attracted a great deal of attention, and, with modifications, are accepted, at least as a working hypothesis, by a fair number of people.

When Sir John Herschel had extended his father's researches into the Southern Hemisphere he was also led to the belief that some nebulae were a phosphorescent material spread through space like fog or mist.

Then his views were changed by the revelations due to the great discoveries of Lord Rosse with his gigantic refractor,[22] when one nebula after another was resolved into a cluster of minute stars. At that time the opinion gained ground that with increase of telescopic power this would prove to be the case with all nebulÃ.

In 1864 all doubt was dispelled by Huggins[23] in his first examination of the spectrum of a nebula, and the subsequent extension of this observation to other nebulÃ; thus providing a certain test which increase in the size of telescopes could never have given. In 1864 Huggins found that all true nebulae give a spectrum of bright lines. Three are due to hydrogen; two (discovered by Copeland) are helium lines; others are unknown. Fifty-five lines have been photographed in the spectrum of the Orion nebula. It seems to be pretty certain that all true nebulae are gaseous, and show almost exactly the same spectrum.

Other nebulÃ, and especially the white ones like that in Andromeda, which have not yet been resolved into stars, show a continuous spectrum; others are greenish and give no lines.

A great deal has to be done by the chemist before the astronomer can be on sure ground in drawing conclusions from certain portions of his spectroscopic evidence.

The light of the nebulas is remarkably actinic, so that photography

has a specially fine field in revealing details imperceptible in the telescope. In 1885 the brothers Henry photographed, round the star Maia in the Pleiades, a spiral nebula 3' long, as bright on the plate as that star itself, but quite invisible in the telescope; and an exposure of four hours revealed other new nebula in the same district. That painstaking and most careful observer, Barnard, with 10Â hours' exposure, extended this nebulosity for several degrees, and discovered to the north of the Pleiades a huge diffuse nebulosity, in a region almost destitute of stars. By establishing a 10-inch instrument at an altitude of 6,000 feet, Barnard has revealed the wide distribution of nebular matter in the constellation Scorpio over a space of 4Â or 5Â square. Barnard asserts that the "nebular hypothesis" would have been killed at its birth by a knowledge of these photographs. Later he has used still more powerful instruments, and extended his discoveries.

The association of stars with planetary nebulÃ, and the distribution of nebulÃ in the heavens, especially in relation to the Milky Way, are striking facts, which will certainly bear fruit when the time arrives for discarding vague speculations, and learning to read the true physical structure and history of the starry universe.

Stellar Spectra.–When the spectroscope was first available for stellar research, the leaders in this branch of astronomy were Huggins and Father Secchi,[24] of Rome. The former began by devoting years of work principally to the most accurate study of a few stars. The latter devoted the years from 1863 to 1867 to a general survey of the whole heavens, including 4,000 stars. He divided these into four principal classes, which have been of the greatest service. Half of his stars belonged to the first class, including Sirius, Vega, Regulus, Altair. The characteristic feature of their spectra is the strength and breadth of the hydrogen lines and the extreme faintness of the metallic lines. This class of star is white to the eye, and rich in ultra violet light.

The second class includes about three-eighths of his stars, including Capella, Pollux, and Arcturus. These stars give a spectrum like that of our sun, and appear yellowish to the eye.

The third class includes Îł Herculis, Îł Orionis (Betelgeux), Mira Ceti, and about 500 red and variable stars. The spectrum has fluted bands shaded from blue to red, and sharply defined at the more refrangible edge.

The fourth class is a small one, containing no stars over fifth magnitude, of which 152 Schjellerup, in Canes Venatici, is a good example. This spectrum also has bands, but these are shaded on the violet side and sharp on the red side. They are due to carbon in some form. These stars are ruby red in the telescope.

It would appear, then, that all stars are suns with continuous spectra, and the classes are differentiated by the character of the absorbent vapours of their atmospheres.

It is very likely that, after the chemists have taught us how to interpret all the varieties of spectrum, it will be possible to ascribe the different spectrum-classes to different stages in the life-history of every star. Already there are plenty of people ready to lay down arbitrary assumptions about the lessons to be drawn from stellar spectra. Some say that they know with certainty that each star begins by being a nebula, and is condensed and heated by condensation until it begins to shine as a star; that it attains a climax of temperature, then cools down, and eventually becomes extinct. They go so far as to declare that they know what class of spectrum belongs to each stage of a star's life, and how to distinguish between one that is increasing and another that is decreasing in temperature.

The more cautious astronomers believe that chemistry is not sufficiently advanced to justify all of these deductions; that, until chemists have settled the lately raised question of the transmutation of elements, no theory can be sure. It is also held that until they have explained, without room for doubt, the reasons for the presence of some lines, and the absence of others, of any element in a stellar spectrum; why the arc-spectrum of each element differs from its spark spectrum; what are all the various changes produced in the spectrum of a gas by all possible concomitant variations of pressure and temperature; also the meanings of all the flutings in the spectra of metalloids and compounds; and other equally pertinent matters–until that time arrives the part to be played by the astronomer is one of observation. By all means, they say, make use of "working hypotheses" to add an interest to years of laborious research, and to serve as a guide to the direction of further labours; but be sure not to fall into the error of calling any mere hypothesis a theory.

Nebular Hypothesis.–The Nebular Hypothesis, which was first, as it were, tentatively put forward by Laplace as a note in his _SystÃme du Monde_, supposes the solar system to have been a flat, disk-shaped nebula at a high temperature in rapid rotation. In cooling it condensed, leaving revolving rings at different distances from the centre. These themselves were supposed to condense into the nucleus for a rotating planet, which might, in contracting, again throw off rings to form satellites. The speculation can be put in a really attractive form, but is in direct opposition to many of the actual facts; and so long as it is not favoured by those who wish to maintain the position of astronomy as the most exact of the sciences–exact in its facts, exact in its logic–this speculation must be recorded by the historian, only as he records the guesses of the ancient Greeks–as an interesting phase in the history of human thought.

Other hypotheses, having the same end in view, are the meteoritic

hypothesis of Lockyer and the planetesimal hypothesis that has been largely developed in the United States. These can best be read in the original papers to various journals, references to which may be found in the footnotes of Miss Clerke's _History of Astronomy during the Nineteenth Century_. The same can be said of Bredichin's hypothesis of comets' tails, Arrhenius's book on the applications of the theory of light repulsion, the speculations on radium, the origin of the sun's heat and the age of the earth, the electron hypothesis of terrestrial magnetism, and a host of similar speculations, all combining to throw an interesting light on the evolution of a modern train of thought that seems to delight in conjecture, while rebelling against that strict mathematical logic which has crowned astronomy as the queen of the sciences.

FOOTNOTES:

[1] _R. S. Phil Trans_., 1810 and 1817-24.

[2] One of the most valuable contributions to our knowledge of stellar parallaxes is the result of Gill's work (_Cape Results_, vol. iii., part ii., 1900.)

[3] Taking the velocity of light at 186,000 miles a second, and the earth's mean distance at 93,000,000 miles, 1 light year=5,865,696,000,000 miles or 63,072 astronomical units; 1 astronomical unit a year=2.94 miles a second; and the earth's orbital velocity=18.5 miles a second.

[4] Ast. Nacht., 1889.

[5] R. S. Phil. Trans., 1718.

[6] Mem. Acad. des Sciences, 1738, p. 337.

[7] R. S Phil. Trans., 1868.

[8] _R.S. Phil Trans._, 1783.

[9] See Kapteyn's address to the Royal Institution, 1908. Also Gill's presidential address to the British Association, 1907.

[10] _Brit. Assoc. Rep._, 1905.

[11] R. S. Phil. Trans., 1803, 1804.

[12] Ibid, 1824.

[13] Connaisance des Temps, 1830.

[14] _R. A. S. Mem._, vol. xlvii., p. 178; _Ast. Nach._, No. 3,142; Catalogue published by Lick Observatory, 1901.

[15] _R. A. S., M. N._, vol. vi.

[16] _R. S. Phil. Trans._, vol. lxxiii., p. 484.

[17] _Astr. Nach._, No. 2,947.

[18] _R. S. E. Trans_., vol. xxvii. In 1901 Dr. Anderson discovered Nova Persei.

[19] _Astr. Nach_., No. 3,079.

[20] For a different explanation see Sir W. Huggins's lecture, Royal Institution, May 13th, 1892.

[21] For the early history of the proposals for photographic cataloguing of stars, see the _Cape Photographic Durchmusterung_, 3 vols. (_Ann. of the Cape Observatory_, vols. in., iv., and v.,

Introduction.)

[22] _R. S. Phil. Trans._, 1850, p. 499 _et seq._

[23] _Ibid_, vol. cliv., p. 437.

[24] _Brit. Assoc. Rep._, 1868, p. 165.

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